A Comparison Between High-Impedance and Low-Impedance Restricted Earth-Fault Transformer Protection

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***Abstract*—Restricted earth-fault (REF) protection on a transformer is a subject for which there has been little attention and, compared to other types of protection, very little literature exists.**

Depending on the method of transformer earthing and fault location, some transformer earth faults result in only a small increase in phase current, which transformer differential protection may not detect. Conversely, the amount of current in the neutral may be sufficient to detect most or all earth faults, again depending on the earthing method. By connecting an REF relay to CTs installed in correct locations on the transformer, one can use REF protection to complement differential protection in detecting transformer earth faults. Obtaining maximum benefit from REF protection requires that one consider many factors, including whether to select high-impedance REF or low-impedance REF relays. In making this selection, one should understand the theory behind each option.

Historically, only high-impedance REF protection was available, because of equipment and technology limitations. Today, numerical protection relays include low-impedance REF elements for transformer protection. Both types of protection have advantages and disadvantages; the relays do not perform equally well in all applications. One key advantage of low-impedance REF protection included in a numerical relay is the ability to use CTs with different ratios and specifications without the need for interposing CTs. One key advantage of high-impedance REF is proven immunity (relay security) to CT saturation for external faults. Key to either type of protection is the ability to provide maximum winding coverage against earth faults. There is also speculation, as yet unsubstantiated, that a high-impedance REF element provides superior sensitivity and coverage against earth faults.

This paper summarizes the theory of classical high-impedance REF protection and new low-impedance REF protection. It also discusses issues such as relay sensitivity requirements, transformer fault current distribution, impact of fault location on relay performance (winding coverage), CT requirements, the impact of CT saturation response on REF protection elements, and application considerations for the two protection methods.

I. Introduction

Power transformers constitute the single most expensive item of primary plant in a substation. To protect this investment properly, transformer protection schemes contain a combination of protection elements, with biased differential protection widely used. Although biased differential protection provides excellent protection for phase-to-phase and most phase-to-earth winding faults, this element is less sensitive for single-phase-to-earth faults close to the earth point in solidly earthed transformers [1], [2], and [3]. For these faults, phase current changes very little, but large current flows in the neutral conductor [1] [2].

REF takes advantage of the large current in the neutral conductor to provide sensitive and fast protection for transformer faults close to the earth point. REF protection applied to transformers may be referred to as "unit earth-fault protection," and the "restricted" part of the earth-fault protection refers to an area defined between two CTs. Generally, REF protection can be applied in one form or another to all transformer windings, even delta-connected windings (see *Delta Winding—NEC/R Earthed*). On solidly earthed star windings, we will show that fault coverage is possible from the first turn above the star point, provided the REF element connects to a CT in the transformer neutral. This high winding coverage is possible because the relay operates on the high fault current in the neutral conductor instead of on the small fault current in the phase. On an unearthed star winding or a delta-connected winding without a neutral earthing compensator (NEC), winding coverage is reduced because of the lack of a neutral CT. Unearthed star windings or delta-connected winding installations provide phase CTs only (see *Delta Winding—NEC/R Earthed*), and the REF element operates on the change in phase current only.

II. Earth-Fault Current and Impact on Sensitivity

A. Earth-Fault Currents in a Transformer for Different Connections

When operating from the neutral CT, REF protection provides more sensitive earth-fault protection than does biased current differential protection. However, many setting engineers are uncertain as to the exact increase in sensitivity that REF protection provides. It is therefore necessary to quantify what one means by "more sensitive." In the following discussion, we investigate the available fault current for star windings (solidly earthed, impedance earthed, and unearthed) and delta windings.

1) Star Winding—Solidly Earthed

For a solidly earthed star winding, an earth fault anywhere on the winding is similar to an autotransformer with a fault on the secondary side. Fig. 1 explains the phenomenon.

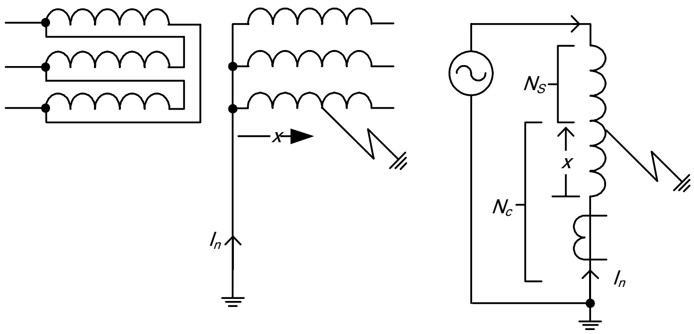

Fig. 1 Solidly Earthed Star-Connected Windings With Earth Fault X Per Unit From the Neutral

From Fig. 1, it can be seen that the turns ratio (T_R) is as follows:

$$T_R = \frac{I_n}{I_p} = \frac{N_c + N_s}{N_c} = \frac{1}{x} \quad (1)$$

and

$$I_n = I_p \bullet T_R = \frac{I_p}{x} \quad (2)$$

Where

- N_c = the number of turns on the common winding (on the shorted part of the winding)
- N_S = the number of turns on the series winding (on the healthy part of the winding)
- x = the distance from the neutral (p.u.)
- I_p = primary side current
- I_n = fault current

Therefore, for faults close to the neutral (when x is very small, on the order of 0.1 p.u.), the current flowing in the neutral is $I_n = I_p/0.1 = 10 \bullet I_p$. Clearly, the change in neutral current is much greater than the change in phase current.

Fig. 2 shows the difference in neutral current and phase current, plotted as a function of the fault distance from the neutral point [1] [2] [3] [4]. This curve was obtained from tests that were performed on a solidly earthed star transformer. (Because results vary for different transformer designs, the authors were unable to locate a formula that accurately describes the theoretical earth-fault current for all transformers). Fig. 2 shows that the neutral current (that also flows through the neutral CT) is always very high, in excess of 5 to 6 p.u.

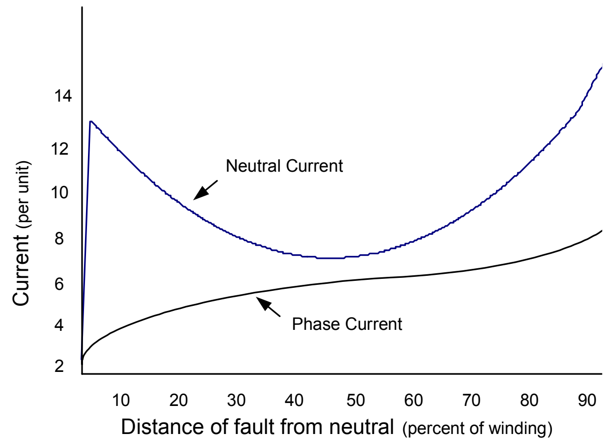

Fig. 2 Neutral Current vs. Distance From Star Point in a Solidly Earthed HV Star Transformer

For faults closer to the phase terminal of the star winding, there is reduced current contribution from the transformer neutral. Relay sensitivity is still not compromised, because the operating current through the relay is the sum of the neutral and phase current, with the phase current now higher than for faults near the neutral.

Therefore, in the case of a solidly earthed star winding, relay sensitivity is not a problem for faults near the neutral because there is always sufficient current flowing in the neutral CT and through the relay and varistor to ensure relay operation.

2) Star Winding—Resistance Earthed

In the case of a resistance-earthed star winding, the relationship between fault location and fault current is linear, and the value of the earthing resistance determines the amount of fault current. From Fig. 1, assuming that the neutral is earthed through a resistor, we can see that the following is true:

$$I_n = \frac{x \bullet V}{\sqrt{3} \bullet R} \quad (3)$$

Where

- I_n = fault current
- x = the distance from the neutral
- V = the healthy phase-to-phase voltage
- R = the value of the earthing resistor

Equation 3 presents a linear relationship between the fault location and the neutral current available to operate the relay. For small values of x, I_n is small and there may not be sufficient current to operate the relay. Therefore, for a resistance-earthed star winding, relay sensitivity is important for faults near the neutral. The value of x where the relay will begin operation is related directly to the relay operating current and the CT characteristics, i.e., how much magnetizing current the CTs on the healthy phases will require.

3) Delta Winding—NEC/R Earthed

In the case of a delta winding, there is always sufficient voltage to drive fault current through the fault and NEC/R. In theory, there is always at least half the phase-to-earth voltage available to drive the fault. This results in sufficient fault current, and relay sensitivity is not an issue [3].

Because delta-connected windings do not have a star point, you can use the so-called balanced earth-fault connection or hybrid REF protection function in cases where the source is on the delta side of the transformer. In this case, the neutral CT is excluded from the circuit and the three-phase CTs are all connected in parallel with the relay element. The zone of protection is still only the delta winding of the transformer.

The balanced earth-fault connection may also be applied to an unearthed star winding.

III. Restricted Earth-Fault Protection Theory

To apply REF protection on star-connected transformers, connect the three-phase CTs in star, and connect this combination to a CT in the neutral leg of the transformer, NER or NEC, as shown in Fig. 3. These CT connections provide a path for the zero-phase sequence currents to circulate in the CTs during external faults, but they force the current through the relay for internal faults. Therefore, the REF relay provides protection for all earth faults that fall in the area between the phase and neutral CTs. Any fault outside this area should be covered by alternative protection functions.

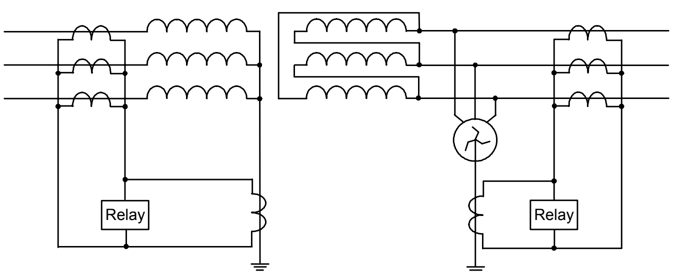

Fig. 3 Basic Design of an REF Function

Fig. 4 shows an external earth fault on the star (source) side of a transformer, and Fig. 5 shows an in-zone fault on the delta side of a transformer. Currents are in per unit. In Fig. 4, the zero-sequence infeed for an upstream red phase-to-earth fault circulates between the neutral CT and the red-phase CT, and no operating current can flow through the relay element. In Fig. 5, in the case of the in-zone fault on the delta winding, it is clear that all the fault current flows through the neutral CT ($I_{Fp} = I_{np}$) and nothing flows in the phase CT. Therefore, the secondary CT current has to flow through the relay element for this element to operate. At this stage, we simplify the scenario by not taking into account the magnetization of the other CTs.

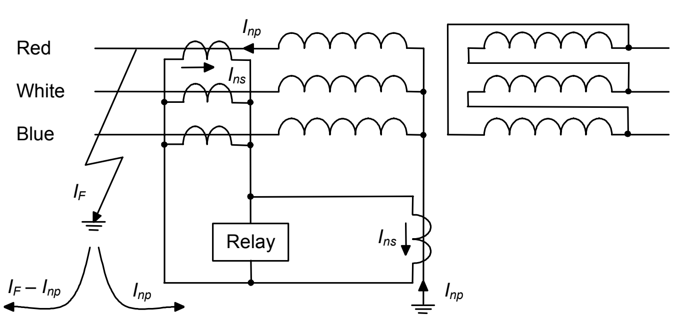

Fig. 4 External Fault Indicating Relay Stability on a Star-Connected Winding

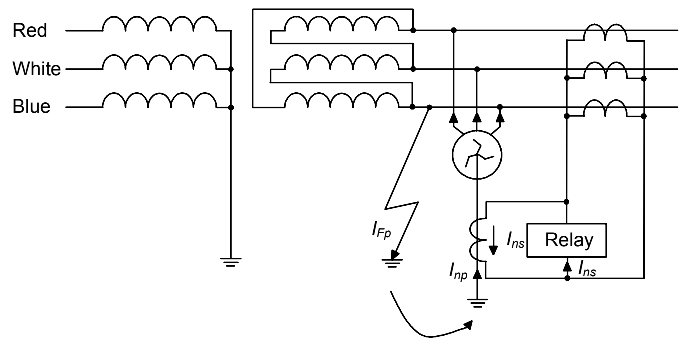

Fig. 5 Internal Fault Indicating Operation on a Delta Winding With NEC

A hybrid REF protection function may also be applied to a delta winding without an NEC. The hybrid REF excludes the neutral CT from the circuit and the three phase CTs are all connected in parallel with the relay element. This is called a balanced earth-fault connection. The zone of protection is still only the delta winding of the transformer. The hybrid REF function can also be applied to an unearthed star winding.

A. High-Impedance REF Relay Element

The high-impedance REF relay is normally a current-operated relay with a resistor in series that provides stabilization. Generally, it may be one of two different types. The first type has internal resistors and has a voltage setting. In this type, the resistors are effectively switched in and out to change the setting and therefore the value of the stabilizing voltage. The second type has an external variable resistor where the setting is calculated in ohms and applied by changing the resistance of the variable resistor.

1) Design Considerations

A number of design considerations must be taken into consideration when designing a high-impedance REF scheme. The most important considerations are described here:

- The ratio of the phase and neutral CTs must always be the same.
- In general, the CTs should have the same saturation characteristics.
- The kneepoint voltage must be higher than the stabilization voltage for external faults.
- The voltage across the relay and CTs (all in parallel) should be kept at safe levels while still being sufficiently high to allow operation of the relay when required. The magnetizing current of the CTs depends on the voltage across it, but too high a voltage results in higher magnetizing current that leads to a less sensitive scheme.
- In most cases, a metal oxide varistor (MOV) or surge arrestor is connected across the parallel connection of the CTs and relay to clamp the voltage to a safe limit, without affecting relay operation. The MOV protects the relay against high voltages developed during in-zone faults. Sufficient current still flows through the relay to ensure operation [5].

2) Setting Considerations

The high-impedance REF scheme is set such that it is stable for a maximum through fault with one of the CTs completely saturated.

Calculate V_S, the stabilizing voltage, as follows:

$$V_s = \frac{I_{f\max} \bullet (R_{CT} + R_L)}{n} \tag{4}$$

Where

V_s = the stabilizing voltage

$I_{f\max}$ = the maximum through-fault current detectable by the relay

R_{CT} = the winding resistance of the CT

R_L = the total lead resistance of the longest conductor between the relay and neutral or phase CTs

n = the turns ratio of the CT

In cases where the earth-fault current is limited through an NER or NEC/R, use the three-phase fault current as the maximum condition. With all four CTs of the same ratio, we expect the phase CTs (not the neutral CT) to saturate for external faults, because the three-phase fault current is higher than the earth-fault current. Therefore, we can ignore the resistance of the leads between the saturated phase CT and the relay. (The saturated phase CT and the relay are not necessarily near each other, so the lead resistances between them are not negligible). Phase CTs are generally located in close proximity to one another, so lead resistances between these CTs are negligible.

V_S is the value of the stabilizing voltage across the relay for maximum through-fault current and one saturated CT. The relay setting, V_{set}, is still unknown. If the voltage applied to the relay exceeds V_{set}, we expect the relay to operate. The most sensitive setting that can be applied is $V_{set} = V_S$. Because network parameters change (higher fault current for example), V_{set} is usually selected higher than V_S to allow for a safety margin.

To ensure greater stability, one would select relay operating current greater than the sum of the healthy phase CT magnetizing currents at the set voltage. This ensures that the largest part of the secondary side fault current is used for the purpose of operating the relay and that less current is used for magnetizing the CTs on the healthy phases.

Any mismatch in CT ratio will result in spill current, part of which will flow through the relay. Spill current cannot be related to current that flows on the primary side and flows on the secondary side. It may, therefore, cause the flow of "fictitious" current that results from CT inaccuracy. Not all spill current will necessarily flow through the relay; some of the current also flows through CTs (phase and/or neutral) not carrying primary fault current. Effectively, the spill current flowing through the relay raises the voltage across the relay and CTs, causing more magnetizing current to flow. In the case of a through fault, equilibrium is reached between the voltage, relay current, and magnetizing current. Generally, relay current is far less than the operating current, as explained in the calculation of the stabilizing voltage.

Another important factor in the design of an REF scheme is the minimum allowable knee-point voltage of the phase and neutral CTs. This value is necessary during the design phase of the high-impedance REF scheme to ensure adequately specified CTs. To ensure that the CT does not saturate at the operating voltage, many engineers use a safety factor of 2. The knee-point voltage can be calculated as follows:

$$V_k = 2 \bullet V_s \tag{5}$$

Where

V_k = the kneepoint voltage of the CT

Calculate I_{op}, the minimum primary operating current (primary sensitivity) that causes the relay to operate, as follows:

$$I_{op} = n \bullet (I_R + m \bullet I_m + I_v) \tag{6}$$

Where

I_R = the relay operating current

m = the number of CTs needing magnetization (generally three)

I_m = the magnetizing current at the set voltage (to be obtained from the magnetizing curve test results of the CTs)

I_v = the varistor current at V_s [5]

From this discussion, it should be clear that the desensitizing factors are the magnetizing current I_m and the varistor current I_v.

Use Equation 7 to calculate the actual impedance of the REF element. Because V_{set} is the voltage above which the relay operates, and because the relay resistance is much greater than R_{CT} and R_L, you can calculate the relay resistance as follows:

$$R_R = \frac{V_{set}}{I_R} \tag{7}$$

Where

R_R = the relay resistance

V_{set} and I_R are as defined above

To verify correct calculation of operating current, it is possible to calculate the voltage across the relay for a specific in-zone fault current. If the voltage is above the set voltage, consider this as confirmation that the relay will operate. You can calculate the operating voltage as follows:

$$V_{op} = \frac{(I_{op} - m \bullet n \bullet I_m - I_v) \bullet (R_{CT} + R_L + R_R)}{n} \tag{8}$$

Because the relay is set to be stable under conditions where one CT saturates, it needs no additional time delays to improve security or its operation.

B. Low-Impedance REF Relay Element

Low-impedance REF protection is provided with new numerical or microprocessor-based protection relays. Generally, relay manufacturers employ different methods to provide REF protection. In most cases, operation of the low-impedance REF protection is based on the fundamental current, after filtering removes all harmonic currents [3].

The most important difference between classical high-impedance REF protection and new low-impedance REF protection is the input impedance. As with all numerical relays, the input impedance of the low-impedance REF is very low compared to high-impedance relays. For example, a low-impedance relay typically has an input impedance of 0.1 VA. At 1 A nominal rating, this computes to 0.1 W. On the other hand, for a high-impedance REF relay with a voltage setting of 100 V and a 20 mA operating current, the input impedance is 5 kW. This is a significant difference.

Low-impedance REF protection does not have the same inherent stability against CT saturation for external faults as does high-impedance REF protection.

A second significant difference is that the operating current of the low-impedance REF protection is not realized by CT connection. With low-impedance REF, the relay measures all four CTs necessary to realize the element. Fig. 6 and Fig. 7 show the wiring and CT connections of the low-impedance REF elements. Fig. 6 shows the fault currents for an external fault on the primary star-connected side of a transformer, and Fig. 7 shows an external fault on the secondary delta-connected side of the transformer.

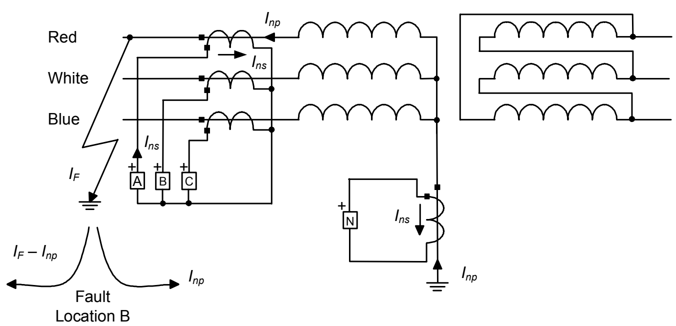

Fig. 6 Low-Impedance REF Connections With External Earth Fault on a Star-Connected Winding

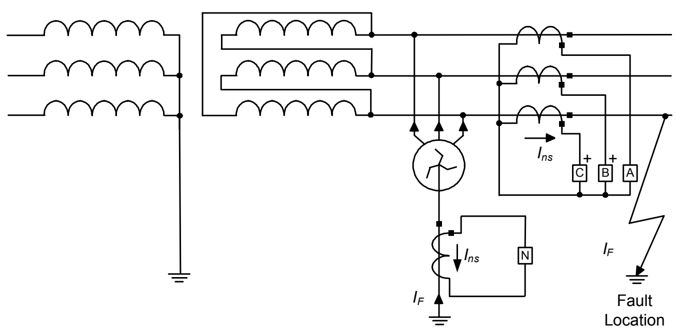

Fig. 7 Low-Impedance REF Connections With External Earth Fault on a Delta-Connected Winding With NEC

Fig. 8 and Fig. 9 show the same relay and CT connections for a low-impedance REF relay. They also show the current flow for in-zone faults on the primary star-connected and secondary delta-connected sides of the transformer, respectively.

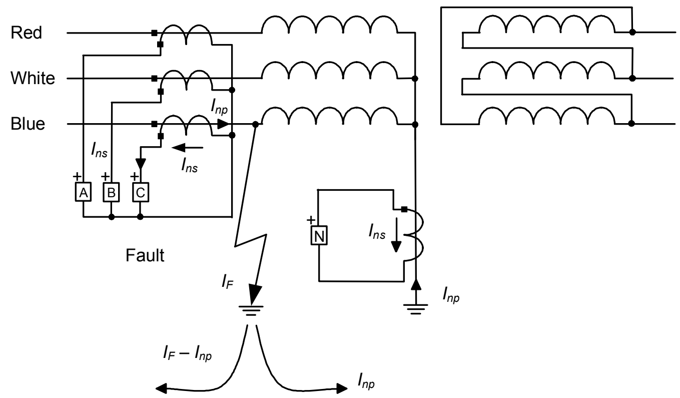

Fig. 8 Low-Impedance REF Connections With Internal Earth Fault on a Star-Connected Winding

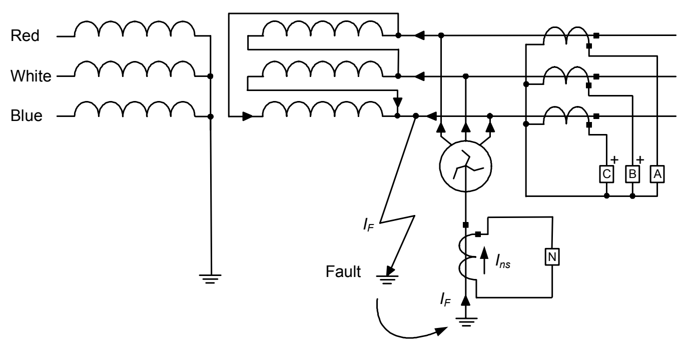

Fig. 9 Low-Impedance REF Connections With Internal Earth Fault on a Delta-Connected Winding With NEC

A very important advantage of low-impedance REF protection is the fact that the CT ratios for the phase CTs and neutral CTs do not have to be the same.

Most low-impedance REF relays use an operating and a restraint current. The difference between different relays from different manufacturers lies in the way these relays determine the restraint quantities and in the CT saturation detection algorithm of each relay. Note that, in the case of low-impedance REF protection, there is no inherent immunity to CT saturation, as is the case with high-impedance REF protection. The following different methods are used to determine the restraint and operating current:

1. Use of the residual current $I_r = I_a + I_b + I_c$ as the restraint current and the differential current $I_d = I_a + I_b + I_c - I_n$ as the operating current. (9)
2. Use of the residual current $I_r = I_a + I_b + I_c$ as the operating current and the neutral current I_n as the restraint current. (10)

From Fig. 7, it may be seen that $I_a = I_b = 0$ for a blue-phase out-of-zone fault on the delta side of the transformer. From this, it is clear that $|I_c| = |I_F| = |I_{ns}|$. From Equation 9 above, one can see that the differential current can be defined as follows:

$$I_d = I_a + I_b + I_c - I_n = 0 + 0 + (-I_{ns}) - (-I_{ns}) = 0$$

and

$$I_r = I_a + I_b + I_c = -I_{ns}$$

This shows clearly that there is restraint current but no differential or operating current for an external fault. From Equation 9 it can be shown that the following relationships are true:

$$I_d = I_{ns} \text{ and } I_r = 0$$

This means that, while there is a large amount of differential or operating current, there is no restraining current. This can be shown similarly for in-zone and external faults on the star side of the transformer.

Because of the nature of the protection, classical low-impedance REF protection cannot be used as a balanced earth-fault protection on an unearthed transformer or on a transformer with only three phase CTs and no neutral CT. In short, it is because the low-impedance REF protection requires a restraint and an operating current, at least one of which is also derived from the neutral CT. When a neutral CT is not provided, a low-impedance REF protection cannot be used to protect an unearthed transformer. However, most numerical relays provide a number of protection elements for each winding. To realize balanced earth-fault protection on an unearthed star-connected transformer or a delta-connected transformer, connect the CTs as explained under *Delta Winding—NEC/R Earthed*, and associate the CT input with an earth-fault element in the relay.

1) Design Considerations

Because of the inherently unstable nature of the low-impedance REF element, it may misoperate during external faults, especially in the case of faults not involving earth as phase-to-phase and three-phase faults, when one of the phase CTs saturates. Various manufacturers of REF protection relays have each developed additional supervision elements to improve security during external faults while improving sensitivity during in-zone faults.

All these relays scale the CT ratios automatically between the phase and neutral CTs to compare the different values on an equal basis.

a) Product A [6] [7]

This relay makes use of the direction change of the operating current for in-zone and external faults. It derives a zero-sequence operating current from the phase CTs ($I_r = I_a + I_b + I_c$) and a polarizing current from the neutral CT (I_n). It then compares the direction of operating (I_r) and polarizing (I_n) currents.

CT saturation logic is necessary to determine whether any existing zero-sequence operating current is from saturation of one or more CTs during a three-phase fault, or from an actual earth fault. CT saturation detection comes from a positive-sequence restraint factor supervising the REF operation. The relay compares the positive-sequence current multiplied by the positive-sequence restraint factor (generally set to approximately 0.1) with the zero-sequence operating current. For earth faults, the positive-sequence and zero-sequence currents are equal, so the result of this comparison will always be a logical 0, indicating no CT saturation. If zero-sequence exists as a result of CT saturation, CT saturation detection asserts whenever the ratio of zero-sequence to positive-sequence current is less than the positive-sequence restraint factor. Using the reasoning that current must flow in the transformer neutral for an earth fault, the relay enables the REF element only if the neutral current exceeds a threshold. Supervising the REF element with the neutral current provides additional security against zero-sequence current in the line CTs resulting from CT saturation.

Therefore, the relay enables the REF element only if the line CTs measure zero-sequence current and if the current in the neutral CT exceeds a pickup setting. The zero-sequence current pickup setting is therefore also the relay sensitivity. The zero-sequence pickup must be set higher than any natural zero-sequence current caused by load, CT mismatch/spill current, or any other unbalance. The minimum operating current of the relay is 5 percent of rated current (I_n).

The directional element then compares the operating (residual phase current) and polarizing (neutral) currents and indicates a forward or reverse direction. A forward direction indication is for an in-zone fault, and a reverse direction is for an external fault. The fault is said to be in-zone when the residual and neutral currents are in phase; it is reversed if the residual and neutral currents are 180° out of phase.

b) Product B

The basic principle of operation for this relay is to compare the residual (restraint) current $I_r = I_a + I_b + I_c$ with the differential current $I_d = I_a + I_b + I_c – I_n$,

Where

I_a, I_b, and I_c =	the respective phase currents
I_n =	the neutral current flowing in the transformer as a result of the fault

The relay compensates internally for the difference in CT ratios between phase and neutral CTs. In addition, the relay has a biased differential characteristic that you can set in such a way that the relay is desensitized for big differences in CT specifications and subsequent quiescent spill current under normal load conditions. In this case, the relay achieves stability for a through fault by increasing the restraint current when it detects a fault.

The bias setting should still be set as sensitive as possible to ensure relay operation for most faults. The biased differential characteristic of this relay has a fixed slope of 1.05 p.u. The relay will trip if 1) I_d / I_r exceeds 1.05 and 2) I_d exceeds the I_d pickup or threshold setting. The purpose of the restraint function is to compensate for CT errors and mismatches and to ensure stability during maximum through-fault conditions. The latter may cause CT saturation, and the bias characteristic provides additional stability against CT saturation.

The relay has a minimum operating current of 5 percent of nominal current, or 0.05 I_n.

c) Product C [8]

Similarly to Product A above, this relay uses the residual current calculated from the three phase CTs where $I_r = I_a + I_b + I_c$ and the neutral current I_n for the REF protection. During an in-zone fault, neutral current will always flow irrespective of the transformer winding connection and earthing arrangement. The residual current depends on the transformer winding connection and earthing arrangement. In this case, if residual current exists, it will be in phase with the neutral current. During an external fault, the neutral and residual currents will be equal in magnitude and 180° out of phase.

The relay uses I_n only as the operating current, and this current is always present during an in-zone fault. The relay provides a stabilizing method for CT saturation for through faults. Both the current magnitude and phase of the residual and neutral currents stabilize the REF protection. The stabilizing or restraint current is defined as follows:

$$I_{res} = k \bullet (|3I_n - 3I_r| - |3I_n + 3I_r|) \quad (11)$$

Where

k = a stabilization factor

I_n and I_r are as defined previously

An examination of Equation 11 for both internal and external faults reveals that there is no effective restraint for internal faults because the value of restraint is always negative for internal faults. Therefore, the relay has maximum sensitivity, and small earth-fault currents can cause tripping of REF protection. The restraint for external faults is always positive and larger than the operating current, if the operating and restraint quantities are either in phase or 180° out of phase. During CT saturation, these angles may be different, resulting in reduced restraint for external faults. To prevent reduction of restraint, the relay calculates the angle between the operating and restraint quantities and then allows operation for a certain angle range and blocks operation for another angle range. For this specific relay, the angle is fixed at 110°. No operation is possible if the angle between the operating and restraint quantities is greater than 110°, irrespective of any other values of operating and restraint current magnitude. The stabilizing factor (k) is equal to 2 and is fixed. The relay provides further supervision by comparing the neutral current with the sum of the magnitudes of the three phase currents and the neutral current. The relay provides a settable pickup and slope and allows tripping above the characteristic.

The relay has a minimum operating current of 5 percent of nominal current, or 0.05 I_n.

d) Product D [9]

The supplier markets this product as an “earth differential function” with an additional directional check. The relay, therefore, uses a typical biased differential earth-fault characteristic supervised by a directional element. The relay calculates the bias and differential current, where the differential current is the vector difference between the neutral current (measured by the neutral CT) and the residual current where $I_r = I_a + I_b + I_c$. The bias current is the highest of the three phase currents and the neutral current. The relay has a base sensitivity range of 5 percent (maximum sensitivity) to 50 percent (minimum sensitivity) for the differential current. This sensitivity value is valid from 0 to 1.25 p.u. bias current. The bias characteristic has two slopes. The first slope is fixed at 70 percent, and the second is fixed at 100 percent. The first slope is valid from 1.25 p.u. to a point corresponding to a 1 p.u. differential current. The second slope is valid beyond 1.25 p.u.

The directional element uses the neutral current as a reference because direction for this current is always the same for both in-zone and external faults. The relay compares the residual current with the neutral current in the vector plane. For an internal fault, the residual and neutral currents are out of phase. For an external fault, the residual and neutral currents are in phase.

For the directional element, the relay compares the second harmonic current in the neutral CT with the fundamental component. If the second harmonic current is greater than a pre-set value, the REF element is disabled. This is a form of second harmonic blocking that provides additional security against operation during inrush but increased dependability during in-zone faults.

The relay has a minimum operating current of 5 percent of nominal current, or 0.05 I_n.

e) Product E [10]

This relay calculates the differential current as $I_d = I_a + I_b + I_c + I_n$ and the residual current as $I_r = I_a + I_b + I_c$. Restraining current is the maximum of the positive-sequence, negative-sequence, or zero-sequence current in the residual current.

During external faults, the zero-sequence component of the residual current provides maximum restraint. The relay calculates the zero-sequence component as the amplitude of the vector difference between the neutral and residual current. During an external fault, the neutral and residual currents are in phase, so the resulting bias will be twice the neutral current. For an in-zone fault, the residual and neutral currents are out of phase so the restraint will be less than the neutral current.

As previously stated, an external phase-to-phase fault can cause misoperation because of CT saturation. The negative-sequence restraining quantity provides maximum restraint during such an external phase-to-phase fault. This relay uses a method where the level of restraint increases after a number of cycles. This method ensures the most sensitive relay operation upon energization of a faulty transformer. When the restraint increases, security improves for external faults.

The positive-sequence restraining quantity is intended to provide maximum restraint during symmetrical conditions such as three-phase faults and load. The relay uses a complicated algorithm to determine the value of the positive restraint component. Discussion of this algorithm is beyond the scope of this paper.

The relay has a conventional bias characteristic with a pickup setting and slope setting. Both settings can be modified.

2) Setting Considerations for Maximum Sensitivity

Some product-specific setting considerations have been discussed previously in this paper.

Most relays have a minimum pickup level of 50 mA. Although all low-impedance REF relays this paper discusses have additional supervision for improved security, many manufacturers recommend a pickup setting greater than the steady-state neutral current resulting from load unbalance (quiescent zero-sequence current). This ensures that the relay picks up for actual faults, not for load unbalance. This practice reduces scheme sensitivity, because a greater operating current setting increases the minimum primary operating current.

In cases where a biased earth differential protection is provided, the bias setting serves mainly to prevent the relay from operating for external faults resulting from CT saturation and other lesser important factors. These characteristics are fairly fixed, and security against operation for external faults is almost guaranteed.

IV. Sensitivity Issues

This paper stated previously that relay sensitivity is not of great concern for faults on either solidly earthed star windings or impedance-earthed delta windings. There is always sufficient current to drive the operating element of the relay to ensure operation.

Factors affecting REF scheme sensitivity are CT quality or specification, the magnetizing current the healthy phase CTs draw during a fault, the relay operating current, and the resistance earthing of the star-connected transformer.

CT performance impacts greatly the sensitivity of the REF element. Lesser-quality CTs can make low-impedance REF protection more sensitive, because the operating voltage is lower and the CTs on the healthy phases draw less magnetizing current.

Equation 6 provides relay sensitivity for both high-impedance and low-impedance REF, with slight variations between the two. The equation is valid for the high-impedance REF sensitivity calculation. In the case of low-impedance REF sensitivity, the varistor current is excluded and the relay does not have an operating voltage. Therefore, the magnetizing current is not the current the healthy phase CTs would draw at the operating voltage. A voltage equal to the sum of the lead and relay resistances multiplied by the fault current would appear across the healthy CTs. The magnetizing current of all CTs at this voltage should be added to the relay operating current to determine the relay sensitivity. The low-impedance REF measuring element will develop a much lower voltage across the healthy CTs and the magnetizing current necessary for those CTs will be substantially less than for the high-impedance REF case. Although the low-impedance REF relay minimum operating current is as much as 50 mA, the reduction in magnetizing current compensates for the greater pickup threshold.

For example, assume that the CTs in a high-impedance REF scheme draw 15 mA magnetizing current at the operating voltage, and the relay operating current is 20 mA. It follows then that the total secondary current should be $4 \cdot 15 + 20 = 80$ mA. The corresponding primary current must drive sufficient operating current through the relay to produce the magnetizing current necessary for the CTs to operate the relay. With a 200/1 CT ratio (impedance-earthed transformer), there is an implied minimum primary operating current of 16 A. For a typical 355 A NER, the only part of the winding that is not covered, assuming zero fault resistance, is the bottom $16 / 355 \cdot 100 = 4.5$ percent.

Taking the same example, assume that the CTs in a low-impedance scheme draw only 2 mA magnetizing current because of the lower voltage across the CTs and the relay draws 50 mA. It follows then that the total secondary current should be $4 \cdot 2 + 50 = 58$ mA. With the same CT ratio and NER as in the previous example, the minimum primary operating current is 11.6 A. Clearly, the low-impedance REF function is more sensitive in this case. However, if the CTs used with the high-impedance REF were of better quality and the magnetizing current were also 2 mA, the high-impedance REF relay would be more sensitive. In this case, (assuming zero fault resistance) the bottom $11.6 / 355 \cdot 100 = 3.3$ percent of the winding is not covered.

The transformer protection philosophy [11] of Eskom Distribution Division requires that the REF sensitivity for resistance-earthed star-connected windings be such that it can be set to pick up for faults between 10 percent and 25 percent of the maximum available earth-fault current for an earth fault on the transformer terminals. With this in mind, one can perform the necessary calculations to determine an adequate CT ratio and whether to apply high-impedance or low-impedance REF protection.

As a general rule of thumb for high-impedance REF protection, the relay operating current should be greater than the sum of the CT magnetizing currents at the set voltage, i.e., more fault current should be used to operate the relay than to magnetize the CTs on the healthy phases. This generally ensures greater stability.

V. Application Aspects

As we concluded previously, sensitivity becomes a concern only on resistance-earthed star windings. It is only in this case that the application of high-impedance vs. low-impedance REF protection must be considered. There are two important factors that may influence the decision.

A. The Quality and Specification of the Available CTs

Good-quality CTs with a very steep and linear magnetizing curve indicate CTs that require very little magnetizing current throughout most of the operating range. Poor-quality CTs require more magnetizing current. Perform calculations according to the specific CTs in use for a specific installation to determine the suitability of high-impedance vs. low-impedance REF protection for the application. Perform this calculation as described under sensitivity issues.

B. The Availability of Matching CT Ratios

If the existing equipment is of such a nature that the same ratios are not available for both phase and neutral CTs, you should use low-impedance REF protection, because this type of protection can handle different CT ratios for phase and neutral CTs. However, if the same ratios are available for both phase and neutral CTs, further investigation should reveal whether high-impedance or low-impedance REF is the most suitable for the application.

VI. Conclusions

There is a general belief among many engineers that the fault current for faults close to the neutral point of a star-connected transformer is very small and insufficient to operate the REF protection. This is true only for resistance-earthed star-connected transformers.

This paper makes no ruling on whether low-impedance or high-impedance REF protection is the better method, but it provides the information and methods for choosing the more appropriate relay for a particular application.

REF scheme sensitivity is a problem only on star windings with resistance earthing, because the fault current is a function of fault position, phase-to-neutral voltage, and earthing resistance value. For faults close to neutral, the fault current is very small. The relay operating current and CT magnetizing current are important in determining the winding coverage.

In cases where there is always sufficient fault current to operate the REF relay, the choice between high-impedance and low-impedance REF is not important. Issues such as available CT ratios for the phase and neutral CTs may dictate the choice.

For poor-quality CTs that require larger magnetizing current than a better-quality CT at the same voltage, the low-impedance REF element is more sensitive. Where you use good-quality CTs, however, the high-impedance REF relay is more sensitive.

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IX. Biographies

Izak van der Merwe obtained his B. Eng (Electrical) degree from the University of Stellenbosch in 1991. He started to work for Eskom in 1993 as a Protection Field Engineer. He is currently a Chief Engineer: Protection Specialist in Resources and Strategy, a Corporate Division of Eskom Holdings Limited. He is responsible for Distribution Division National Contracts for protection schemes and equipment, general protection technology direction setting and technology management, and the implementation of Distribution Automation and Substation Automation in Eskom's Distribution Division. He has authored a number of protection and substation automation related papers. He is a Registered Professional Engineer in South Africa.

Casper Labuschagne earned his Diploma (1981) and Masters Diploma (1991) in Electrical Engineering from Vaal Triangle Technicon, South Africa. After gaining 20 years of experience with the South African utility Eskom, where he served as Senior Advisor in the protection design department, he began work at SEL in 1999 as a Product Engineer in the Substation Equipment Engineering group. Presently, he is Lead Engineer in the Research and Development group. He is registered as a Professional Technologist with ECSA, the Engineering Counsel of South Africa, and has authored and co-authored several technical papers.