New Directional Protection for Distribution Networks

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***Abstract*—Directional elements need to be able to differentiate between load current and fault current when two sources are present in the distribution network (closed-loop). When the fault current is about two- or three-times the load current, this is easy to accomplish. But when the directional element is used in a relay that is protecting a distributed generator (DG) the fault and load current may be within the same range, and the direction to the fault still need to be identified. A new directional element for the phase overcurrent relay is proposed to achieve this using individual phase torques and the negative sequence torque. Yet a bigger contribution of this paper is deriving the minimum pickup thresholds for correct operation of the proposed directional element.**

***Index Terms*—Directional overcurrent relay, distribution network protection, closed-loop networks, distributed generation, symmetrical components.**

I. Introduction

To determine fault direction, directional elements use the concept of torque. In digital relays the torque is computed with the current and voltage phasors, which are in turn calculated using discrete Fourier transform from the output signals of the current and potential transformers of the relay. See [1] for more details. There are six basic torques that are commonly used – a phase torque for each of the three phases, and the positive, negative, and zero sequence torques. The latter three are computed with the symmetrical components of the current and voltage phasors. See [2] for the definition of symmetrical components and for an in-depth analysis of how the different components behave under different fault conditions. Yet despite the limited number of torques, and the existence of digital (or numerical) relays since the early 1980s, a directional element that is considered an industry standard has not emerged. Different manufacturers, such as [3], [4], and [5], use different torques in their directional elements.

In [6] the limitations of the individual phase torques with a particular 90° torque angle, and of the positive sequence torque in general, are discussed. See also [7] which specifically addresses DGs. To address these limitations the use of the negative sequence torque is suggested and analyzed in [6]. The directional element presented here also uses the negative sequence torque for many of the imbalanced faults. But when the negative sequence torque cannot be used reliably, which is more likely to occur when a DG needs to be isolated from a fault, individual phase torques are used.

Of particular concern with DGs is how low the pickup thresholds can be set above nominal load current. Surprisingly the answer to this, which depends on the particular implementation of the direction element, does not appear in the literature. The applicable IEEE Standard [8] specifically states that it does not cover the application of directional overcurrent relays. The first steps in answering this question are therefore presented here. These steps are somewhat involved and not expected to be used directly when setting up a protection system. However, the theoretical basis presented here will lead to practical engineering guidelines. The analysis is tailored to the specific directional element presented here, but it can be extended to other implementations as well.

A. *Notations and Model Assumptions and Parameters*

Faults in this paper are classified as SLG (single line to ground), L-L (phase to phase), DLG (double line to ground), and 3PH (3-phase). The subscripts 0, 1, and 2 are used to denote zero, positive, and negative sequence, respectively. As the distribution network is of interest here, a wye- (or delta-) connected source or load means that its transformer has a wye (or delta) connection on the side of the distribution network.

For the examples in this paper we use typical 12.47 kV, 60 Hz systems, with 795 ACSR overhead conductors. All sources are modeled as constant voltage (infinite bus) behind the source transformer. Transformer impedance is 8% (0.5% resistive), with no impedance between the wye's neutral and ground. Loads are modeled as constant impedance. Note, however, that the phenomena we describe can be encountered on many other configurations of system voltage, conductor type, circuit topology, and load response.

II. Limitation of Sequence Torques for Phase Overcurrent Relay

A. *Torque Definition*

All the different torques are defined using the same torque function, $T(i, v, \theta) \doteq \Re\left(v \cdot i^* \cdot \exp\left(-j\frac{\pi}{180}\theta\right)\right)$, where $\Re$ is the real part of a complex variable, and θ, given in degrees, is referred to as the maximum torque angle (MTA). The torques differ in the current, voltage and MTA used as inputs: Phase ‘a’ torque is computed as $T(i_a, v_a, \theta_p)$, the zero sequence torque is computed as $T(i_0, v_0, \theta_0)$, etc. Typically θ_p and θ_1, the MTAs for the phase torques and the positive sequence torque, respectively, are set between 0° and 90°, while θ_0 and θ_2, lie between 180° and 270°. A positive torque implies the fault is in the forward direction and a negative torque implies the fault is in the reverse directions. The physical orientation of these directions is based the polarity of the current sensor. Refer to [9] for more about the definition and use of torque.

B. Positive Sequence Torque

While each of the three phase torques is computed directly from the phase current and voltage, the positive sequence is computed from the positive sequence current and voltage. Its sign usually equals the sign of the average taken from the three phase torques. Consider the example of Fig. 1. Under normal conditions the DG supplies 75 A per phase, well below its rated current of 140 A. (140 A per phase is also the load total consumption.) During the fault, however, the current from the DG rises to 190 A on the faulted phase. Since the DG can supply its adjacent load, at least temporarily, there is benefit in interrupting the circuit at the location of the relay.

When looking at the current vs the voltage on phase A, the faulted phase, it is apparent the current flows toward the fault. However, the positive sequence current lags the positive sequence voltage by 45°. With any plausible MTA, this would be considered forward current toward the DG. The positive sequence torque in this case is therefore not sensitive enough to determine the fault direction.

C. Negative Sequence Torque

The negative sequence torque is the preferred tool to detect the fault direction for imbalanced faults. Even in radial networks, where the positive sequence torque always points downstream regardless of the fault direction, the negative sequence torque in the majority of cases points toward the fault. Note that the directional element may still be needed in radial networks operating under an open-loop scheme. The cases where the negative sequence torque may not point toward the fault can be divided into the following categories:

1) *Sensor noise*: When the negative sequence voltage is low and it is calculated from the three phase voltages, small sensor noise may render it unreliable.

2) *Three-phase faults*: Probably the most common situation in which the negative sequence torque does not point toward the fault. The negative sequence torque in this case points to the direction where the load is more imbalanced, regardless of the fault location.

3) *High-impedance fault vs. imbalanced load*: If the negative sequence voltage is affected more by the load than by the fault, the negative sequence torque may point toward the load regardless of the fault location.

The negative sequence torque may also not point toward an upstream fault in a radial network with a highly imbalanced load downstream, but this is very unlikely.

D. Zero Sequence Torque

The zero sequence torque may provide the wrong direction in all the cases listed above for the negative sequence torque. But there are two additional important categories which specifically affect the zero sequence torque.

1) *Phase-to-phase faults*: The fault draws no zero sequence current. The zero sequence torque will point to where a wye-connected load or a group of single-phase loads is more imbalanced, regardless of the fault location.

2) *Delta-connected source in a grounded system*: This applies when the relay is between a wye-connected, grounded, source on one side, and a delta-connected source on the other side. A fault between the grounded substation and the relay can result in significant zero sequence *voltage* being detected by the relay. However, little zero sequence *current* will be detected. Furthermore, with the current being mostly capacitive, the zero sequence torque will point away from the fault.

E. Phase Torque

The individual phase torque values are not susceptible to the problems detailed above for the positive, negative and zero sequence torque. In particular, they change with all types of faults, are much less affected by sensor noise, and crucially, more sensitive than the positive sequence torque.

However, the phase torque does have its limitations. As with the other torques, the difficulty arises when there is a fault on one side of the relay, but in normal conditions the current is serving load on the other side. It is possible for the current in either the faulted or un-faulted phases to increase, sometimes significantly, without changing the torque sign. These cases are listed in §V, where it is also shown how to adjust the pickup thresholds in order to address them.

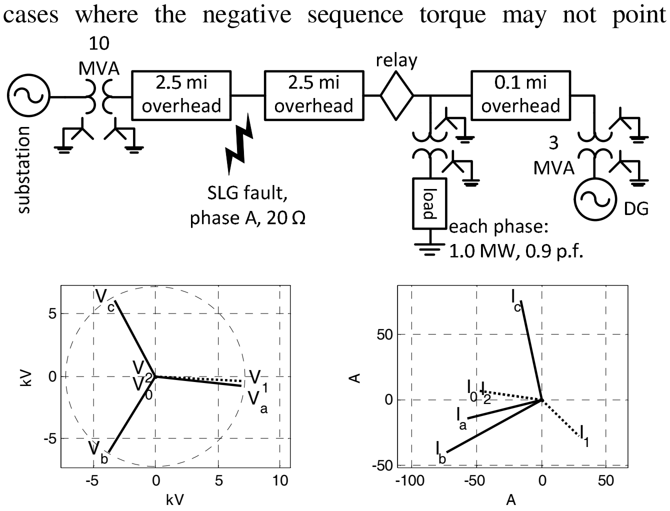

Figure 1. Comparing the sensitivity of the phase torque, which points toward the fault, versus the positive sequence torque which still points toward the load. The continuous lines represent the phase quantities and the dotted lines represent the symmetrical components quantities. The round circle in the voltage plot marks the nominal line-to-neutral voltage.

III. Directional Element for Phase Overcurrent Relay

Based on the discussion in the previous section the directional element of Fig. 2 is proposed. The negative sequence torque is used if the negative sequence voltage is sufficiently high, in which case none of the caveats of §II.C apply. When

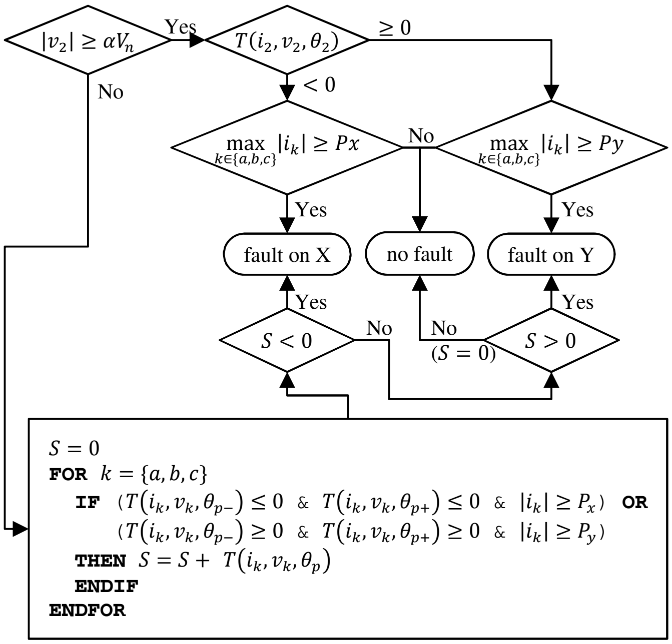

Figure 2. Directional element logic to be used with phase overcurrent relay. The two sides of the relay are identified by side X and side Y. The polarity of the current transformer (CT) is such that current flowing from side X to side Y will result in a positive phase torque. α is a predetermined fraction, and V_n is the nominal phase-to-neutral voltage. Px and Py are the phase current pickup thresholds when protecting against faults on side X and side Y, respectively. The function T, and the angles θ_p and θ_2, are defined in §II.A., θ_{p-} and θ_{p+} define restricted slices of less than 180° ($\theta_{p-} \leq \theta_p \leq \theta_{p+}$, see Fig. 3).

the negative sequence voltage is relatively small, the phase torques are used for their increased sensitivity over the positive sequence torque. However, when using the phase torques, the "slices" of the phasor diagram which determine the current direction are restricted to less than 180° (Fig. 3). By limiting these slices, lower pickup thresholds can be used more reliably as explained in §V.

In certain special cases low-impedance, high X/R, SLG or 3PH faults may not be detected by the logic of Fig. 2. For this to happen the negative sequence voltage must remain low, and the current phasor needs to appear outside the restricted slice. The current phasor will appear outside the restricted slice only if there is sufficient load on the other side of the relay from where the fault is. The negative sequence voltage will naturally remain low for 3PH faults, but these faults are easy to identify as all phase torques in this case will point toward the fault. Additional logic can then be added to Fig. 2 to detect these faults. The negative sequence voltage might also remain small for a SLG fault if the fault is very far from the relay. Most likely none of the positive, negative and zero sequence torques can be used in this case to find the fault direction. Another protection device closer to the fault may then need to be relied upon to interrupt the fault.

IV. Limitation of Using Ground Relay in Multi-Sourced Networks

The ground current is very useful for detecting high-impedance faults, when the fault current may be smaller than normal load current and therefore cannot be detected by the phase overcurrent relay. This is especially true when all load is connected phase-to-phase, or through a delta connection. In

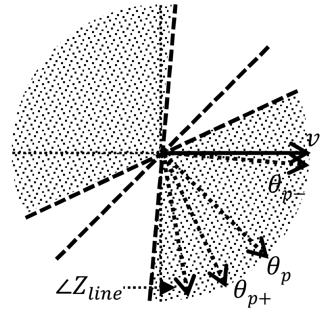

Figure 3. Visualization of the angles defined in Fig. 2. All the angles are with respect to the voltage phasor. If any of the phases has its current phasor in either one of the two shaded areas, its phase torque will be added to the variable S. Each of the shaded area is the intersection of two half-pies defined by the angles θ_{p-} and θ_{p+} at their centers. The contribution of these angles to lowering the minimum pickup thresholds is explained in §V.

that case no ground current is expected, so even a small amount of ground current is an indication of a fault. However, one still needs to find out in which direction the fault lies. The natural choice would be to use the zero sequence torque. And for that both the zero sequence current and the zero sequence voltage need to be higher than the sensor noise.

If the zero sequence component is calculated from the three phase values rather than measured directly, and if the phase values have for example 1% error, the zero sequence component generally needs to be around 3-4% or more of the phase value for the zero sequence torque to be reliable. This number depends on the underlying error distribution, the desired reliability, and how close the angle $\angle v_0 - \angle i_0$ is to θ_0 (or $\theta_0 - 180°$), the MTA for the zero sequence torque.

Setting the ground (three times the zero sequence) current pickup threshold to around 10% of normal load current is usually not considered a limitation. Setting it to ensure 4% of zero sequence of voltage can be a limitation. In an overhead network the ground pickup threshold can be as low as 70 A at 2 miles from a 2 MVA substation, and as high as 900 A at 0.2 miles from a 40 MVA substation. In an underground network these thresholds can rise to 130 A and 2.5 kA, respectively.

In radial networks, if ground current above the level expected to serve the load is detected, and the zero sequence voltage is very low, then the fault must be downstream. The phase torque can then be used to determine the downstream direction. This point is utilized by the proposed directional element in Fig. 4 for a ground overcurrent relay. With it the high current levels from the previous paragraph are of no concern when setting up a radial network. They are of concern, however, when setting up a multi-sourced network.

Take for example the feeder in Fig. 5. With the fault in the diagram the relay measures 170 A of ground current and 200 V of zero sequence voltage. 200 V is 3% of the nominal phase-to-neutral voltage. By the logic of Fig. 4, if the ground pickup for protecting against faults between the substation and the relay (left-side faults) is set to less than 170 A, the relay will trip using the left-side settings (time-current curves, etc.). For right-side faults to result in 4% zero sequence voltage, 245 A of ground current needs to be measured by the relay; 245 A is then the minimum ground pickup for protecting against left-side faults. How high is 245 A? With a 10 Ω SLG fault at the location of the load the DG will supply 180 A on the faulted phase, or 200% of its rated current. This current magnitude could easily be picked up by the phase overcurrent relay if set according to the guidelines of §V. However, the relay will only measure 110 A of ground current. The ground relay is therefore not beneficial in protecting against left-side faults.

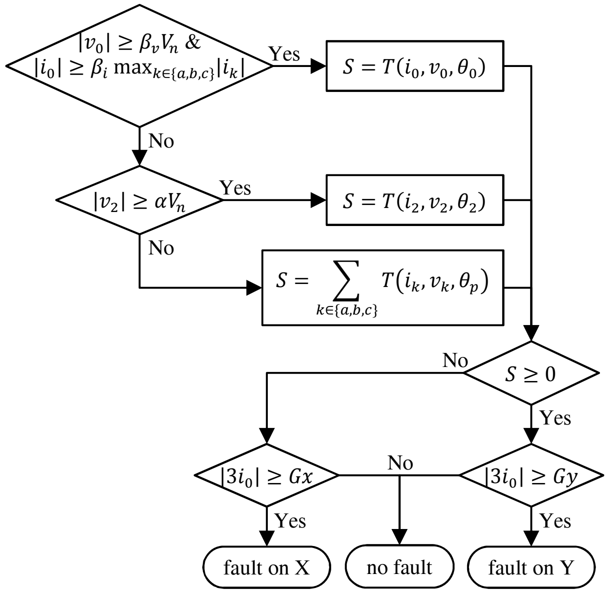

Figure 4. Directional element logic to be used with ground overcurrent relay. See the caption of Fig. 2 for many of the notations. Gx and Gy are the ground current pickup thresholds when protecting against faults on side X and side Y, respectively. β_v and β_i are fractions predetermined by the sensor noise. It is assumed here that the voltage sensor error is proportional to the nominal system voltage, whereas the current sensor error is proportional to measured current.

Setting the ground pickup threshold for protecting against right-side faults to at least 95 A, and disabling left-side protection, will guarantee that the relay will not trip for any left-side faults. However, if during the fault the sum of phase torques is negative, the relay may only trip for right-side faults that register more than 245 A. Note that right-side faults that generate 245 A of ground current may draw only 210 A from the substation, compared to the substation rated current of 925 A per phase. So for protecting against right-side faults the ground relay is beneficial.

V. Determining Minimum Pickup Thresholds for Phase Overcurrent Relay

It is assumed in this section that the pickup threshold for protecting against faults on side Y of the relay is being set. The first thing to consider when setting this threshold is how much current may flow from the source on side X to the load on side Y. This mainly depends on how much load there is on side Y. Capacitor banks, and voltage angle differences between the sources, may increase or decrease this flow and should also be considered. Obviously the pickup threshold must be higher than this current flow, plus some additional safety factor. In many cases, however, this is not sufficient.

Assume current is normally flowing through the relay to side Y. A high impedance fault on side X may increase the current magnitude, but keep the torque sign pointing toward side Y. Items 1–6 below calculate for different X-side faults the maximum phase current magnitude for which the directional element still determines the fault to be on side Y. Item 6 is split to 6a and 6b, which cannot both be applicable at the same time. Setting the pickup threshold higher than the maximum of all the items applicable to the system will assure correct operation of the directional element.

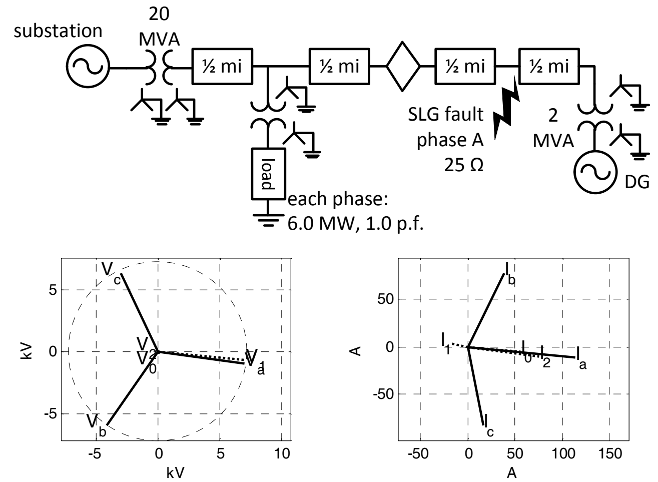

Figure 5. An example where a relatively high ground pickup is required to prevent tripping when the fault is detected to be on the wrong side.

A. SLG or 3PH Fault, Current Increase on Faulted Phase

On a faulted phase, the current can rise to the maximum of the following without changing the torque sign (see Fig. 6):

1) Maximum current which may flow to serve the load on side Y from the source on side X.
2) The current magnitude at the point where the most capacitive fault current, added to the most inductive load current, intersects the $\theta_p + 90°$ line.
3) The current magnitude at the point where the most inductive fault current, added to the most capacitive load current, intersects the $\theta_p - 90°$ line.

The most inductive fault current is the one associated with a very low impedance fault. In general the angle of this current will be determined by the line's X/R ratio. The only exception is when the fault is very close to the substation, in which case the transformer X/R ratio will be more dominant. The most capacitive fault current is the one associated with a high impedance fault next to the X-side source. It will lead its voltage by up to the following angle:

$$\angle Z_{s1} - \angle(Z_{s1} + Z_{s2} + d \cdot Z_{line}), \quad (1)$$

where Z_{s1} and Z_{s2} are the impedance of the sources on side X and side Y, respectively, Z_{line} is the line impedance per unit length, and d is the distance between the two sources. This angle will be close to zero for overhead lines with X/R similar to that of the X-side source transformer, but it can be significantly higher for underground cables with relatively low X/R.

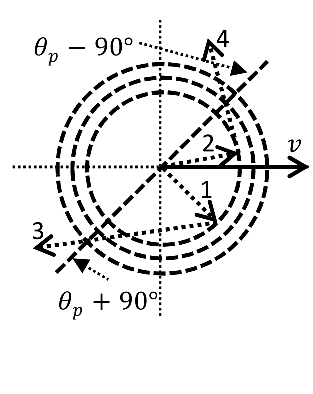

Figure 6. Visualization of the three items for calculating the maximum current in §V.A. Current phasors labeled 1 and 2 in the diagram represent the most inductive and the most capacitive current servicing load on side Y, respectively. Current phasors 3 and 4 represent the most capacitive and the most inductive fault current, for a fault on side X. The radiuses of the smallest, largest, and mid-sized circles are the values of items 1, 2, and 3, respectively, from the list in §V.A.

B. Phase-to-Phase Fault

This fault is divided into three sub-types: high-impedance; low-impedance, far from the relay; low-impedance, close to the relay. For the third sub-type, the current may lag the voltage on one of the faulted phases by up to 180° if the line's X/R ratio is high. However, this will always be associated with significant negative sequence voltage that will trigger the use of the negative sequence torque. It is therefore not of concern when considering its effect on the phase torque.

The maximum current to which the phase current may increase without changing the torque sign, given the two other sub-types, is the maximum of the following:

4) *High-impedance fault*: The current magnitude at the point where a "capacitive" fault current at a leading angle of 30°, added to the most inductive load current, intersects the $\theta_{p-} + 90°$ line.

5) *Far, low-impedance fault*: The current magnitude at the point where an "inductive" fault current at a lagging current of $30° + \angle Z_{line}$, added to the most capacitive load current, intersects the $\theta_{p+} - 90°$ line.

Item 5 should be considered only if the source is strong enough and far enough from a possible fault location to sustain such a fault without experiencing significant negative sequence voltage at the relay location.

For both Item 4 and Item 5 the point where the combined load and fault current intersect the boundaries of the restricted Y-side slice is determined. In §V.A the intersection with the full 180° slices is determined. Measuring the intersection of fault current with the full 180° slices is needed in §V.A only if additional logic (see remark at the end of §III) is added to Fig. 2. Such logic, however, should not apply to L-L faults. With L-L faults, on one phase the fault current is lagging its voltage by between 0° and 60°. The torque on this phase will point toward side X (where the fault is) if the current on the other phase is high enough to be picked up by the Y-side settings.

C. SLG Fault, Grounded Source on Side X and Floating Source on Side Y, Current Increase on Un-Faulted Phase

There is no ground source between the X-side fault and the floating source, where the relay is located. The current feeding the fault from the floating source must then be matched by an opposite current on the other, un-faulted, phases. For a high-impedance fault, this current will appear to be in the direction of the fault, with a leading angle of 60° on one phase and a lagging angle of 60° on the other phase. It is the leading angle of 60° that is of concern. The pickup threshold would then also need to be higher than:

6a) The current magnitude at the point where a "capacitive" fault current at a leading angle of 60°, added to the most inductive load current, intersects the $\theta_{p-} + 90°$ line.

D. SLG fault, Floating Source on Side X and Grounded Source on Side Y, Current Increase on Un-Faulted Phase

As in the previous scenario, the current feeding the fault from the floating source must be matched by an opposite current on the other, un-faulted, phases. However, now the floating source is on the other side of the fault from where the relay is. With the angle the current on an un-faulted phase makes with its voltage, the current may increase indefinitely without changing the phase torque to point toward the fault.

In contrast with the scenario of §V.C, however, the relay will now sense ground current feeding the fault. And as explained in §IV, the ground relay is beneficial for detecting SLG faults in this direction. In the worst case, where the fault is just next to the floating source, the current on the un-faulted phases, i_u, is related to the current on the faulted phase, i_f, according to

$$i_u = \frac{Z_g + d \cdot Z_{line,1}}{Z_g + d \cdot Z_{line,1} + Z_f} i_f \doteq \gamma \cdot i_f, \tag{2}$$

where z_g and z_f are the grounded transformer and the floating transformer impedance, respectively, $z_{line,1}$ is the line's positive sequence impedance per unit length, and d is the distance between the two sources. If the ground relay is set to pick up on X-side faults that carry at least Gx amperes, then the phase pickup threshold would need to be higher than:

6b) The maximum load current, added to:

$$(\gamma/(2\gamma + 1))Gx. \tag{3}$$

VI. CONCLUSIONS

A new directional element for a phase overcurrent relay is proposed. It uses the negative sequence torque and the individual phase torques. The latter provide better sensitivity than the positive sequence torque when more than one source is present in the network. The minimum pickup thresholds needed to guarantee correct operation of the directional element were derived. Higher minimum pickup thresholds may be required if floating sources are present in a grounded network. The special limitations of using a directional ground relay in multi-sourced networks, especially if underground cables are used, were also presented here. Despite these limitations, a ground relay was shown to be very useful in lowering the minimum pickup thresholds for the phase overcurrent relay when floating sources are present.

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