Directional Ground and Sensitive Ground Fault Settings,
Cooper Form 5 and Form 6 Controls and Idea™ Relay,
Three-Wire Distribution Systems

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Abstract:
Ground protection on three-wire distribution systems will vary significantly depending upon the type of grounding implemented on the system. The settings for ground protection in the Cooper Form 5 and Form 6 controls and the Idea™ relay will also be different based on the applied method of grounding. Examples of how each is set for a four-wire, multiple-grounded system will not assist in setting the controls for most three-wire systems. Also, the settings used on one type of three-wire system can vary from another three-wire system that is grounded in a different manner. Therefore this paper will provide examples of typical settings of the Cooper Form 5 and Form 6 controls and the Idea relay for ground protection on each of the different three-wire systems and the potential transformer wiring for these controls.

The different methods of grounding three-wire distribution systems discussed include ungrounded, high-resistance grounded, low-resistance grounded, reactance grounded, and solidly grounded systems. For other methods, identify which one of these is closest to that method and fine-tune for any differences. For each method of grounding, the configuration of the system is described, the settings for conventional ground protection in the Cooper Form 5 and Form 6 controls and the Idea relay is detailed, and the settings for directional protection in each control is detailed. Finally, the connection to a three-wire distribution system of either one or three potential transformers and the associated settings for both of the Cooper controls is explained.

Directional Ground - Torque Angle:
A standard overcurrent protection element will activate its protection regardless of the monitored angle between the voltage and the current, but directional protection will act only within a specific angle. This angle is called the direction of the current. Because mechanical relay elements were first used for directional protection, the activating angle between the current and the voltage is called the torque angle. This is true for the sensitive ground fault (SGF) element as well as the phase overcurrent element.

When voltage leads current, it is called a capacitive torque angle; when the current leads the voltage (or voltage lags current), it is called an inductive torque angle. The maximum torque angle (MTA) is that angle for which the protection element will have the maximum affect. The torque angle width is the range of torque angles for which the directional element will have any affect at all. This is commonly specified as both positive and negative from the MTA, usually ±90 degrees, or a total torque width of 180 degrees. There is no tripping for fault currents detected outside the torque width.
Three-Wire Ungrounded Systems:

**Description:** In a three-wire ungrounded system, no neutral wire is run with the three-phase conductors nor is the transformer grounded at the substation. This means that three-phase system voltages are completely floating with respect to the earth ground. Ground fault currents, with no direct ground path, will flow through the natural capacitance of the system. Natural capacitance occurs between the conductors and ground and through the various device insulation throughout the distribution system. Current in the faulted phase will have a more direct path to ground with very low voltage, while the current in the unfaulted phases will flow to ground through the natural capacitance. Therefore the current will lag the voltage. Note that ground faults on an ungrounded system will cause the resultant system voltages to increase by the square root of three.

**Ground Protection:** The ungrounded system has no direct, resistive, or reactive connection to the earth ground or the neutral of a distribution system. This means that fault currents are very low. One of the strengths of an ungrounded system is that faults carry very low current and so cause minimal damage. However, note that the system voltage may increase during a fault, causing damage to the various device insulations. Because of the need of protection to the insulation on an ungrounded system, it is often considered important to detect very low fault currents. To do this, an SGF element, set to a very low current value, is required. See Figure 1 for example settings of the Form 5 and Form 6 controls and the Idea relay.

**Directional Ground Protection:** An ungrounded system has no direct path to ground. Therefore, ground currents from a fault on one particular feeder will often flow through a neighboring, or even a distant, feeder back to the substation. With ground protection on ungrounded systems set very low, it is common for system protection on one feeder to trip for faults on another feeder, causing

![Form 5 Control](image)

![Form 6 Control](image)

![Idea Relay](image)

**Figure 1.**
Sensitive ground fault settings for ungrounded, resonant-grounded, or high-resistance grounded systems.
unnecessary outages. Known as sympathetic tripping, it can be reduced or eliminated by using directional ground protection. When the directional SGF element is set to the forward direction, it will trip for faults only on that feeder and ignore the reverse current from faults on other feeders.

To set the directional ground protection elements, it is important to know the expected MTA of the faults. Because ungrounded fault currents must flow through device insulation or air gaps, the voltage will lead the current. The MTA for three-wire ungrounded systems should be set with a 90 degree capacitive angle. See Figure 2 for example settings for the Form 5 and the Form 6 controls and the Idea relay. For the Form 5 control, this requires an MTA setting of +90 degrees. The Form 6 control and the Idea relay require an MTA setting of -90 degrees, entered via the Idea software and version 4.0 of the Form 6 control software. Version 3.2 software, however, requires entering +90 degrees with a torque width of "Direction Reverse." Note that the Form 5 directional SGF element uses zero sequence voltage (V0) for polarization (or torque angle reference). During a fault, the system voltage can collapse to a low value. The Voltage Threshold, required only on the Form 5 control for polarization, is typically set to 1–2% of rated voltage, depending on the level of noise in the system. The Form 6 control and the Idea relay use negative sequence voltage (V2) as polarization.

Note also, if the MTA setting of the version 4.0 of the Form 6 control is set to a negative phase angle, that the MTA may not be usable for directional phase or negative sequence directional protection at the same time as directional ground protection.

![Figure 2. Protectional ground settings for three-wire ungrounded systems.](image-url)
Three-Wire Resistively Grounded Systems, Low Resistance:

Description: In a three-wire distribution system resistively grounded with a low level of resistance, no neutral wire is run with the three phase conductors, but the transformer is grounded at the substation through a low level of resistance. Low-resistance grounding limits ground fault currents to a higher level, usually between 50–600 A. It is used to limit the fault current, yet still allow for some ground fault detection and clearing. Only the substation transformer is resistively grounded, so ground currents must flow from the fault through the earth to reach the transformer. There is wide disparity in the fault levels occurring, depending on the distance of the fault from the substation, the local resistance of the earth, and of course the resistance of the fault itself.

Ground Protection: Since the transformer is directly grounded through a low resistance, fault currents tend to be high, especially close to the substation. Note that the resistance is planned so that the fault currents are limited to a calculated value. Normal ground protection set to a higher value above 30 A is sufficient. See Figure 3 for examples of ground protection settings on the Form 5 and Form 6 controls and the Idea relay.

Figure 3. Sensitive ground fault settings for low-resistance grounded systems.
Directional Ground Protection: Low-resistance grounding on a three-wire distribution system is used to allow a good level of fault detection and protection while still limiting its magnitude. For this reason directional protection is not always necessary. When it is necessary or desired, the MTA can be set close to zero. Since the direct link to ground is designed to be predominantly resistive, the fault current in a resistively grounded system tends to be more in phase with the voltage than in an ungrounded system. Therefore the fault angle between current and the voltage is usually close to zero. The torque angle of the directional protection can then be set to zero or a slightly capacitive value. A capacitive value is a positive MTA for the Form 5 control and a negative MTA for the Form 6 control and the Idea relay. See Figure 4 for examples of setting directional ground protection for the Form 5 and Form 6 control and the Idea relay. Note that the Form 5 directional SGF element uses zero sequence voltage (V0) for polarization (or torque angle reference). During a fault, the system voltage can collapse to a low value. The Voltage Threshold, required only on the Form 5 control for polarization, is typically set to 1–2% of rated voltage, depending on the level of noise in the system. The Form 6 control and the Idea relay use negative sequence voltage (V2) as polarization.

![Directional Ground Protection Diagram](image)

**Figure 4.**
Protectional ground settings for three-wire, low-resistance grounded systems.
Three-Wire Resistively Grounded Systems, High Resistance:

Description: In a three-wire distribution system resistively grounded with a high level of resistance, no neutral wire is run with the three phase conductors, but the transformer is grounded at the substation through a high level of resistance. The accepted practice uses a value of resistance equal to the total system capacitance to ground. High-resistance grounding severely limits the fault current so that the damage from a fault is very limited. Only the substation transformer is resistively grounded, so that ground currents must flow from the fault through the earth to reach the transformer.

Ground Protection: Since the transformer is directly grounded through a high level of resistance, ground fault currents will be low, as low as 1–10 A. Because of this, an SGF element is often required. It is set to a low current value, often less than 10 A. See Figure 5 for example settings of the Form 5 and Form 6 controls and the Idea relay.

Directional Ground Protection: Since the direct link to ground is designed to be predominantly resistive, the fault current in a resistively grounded system with a high value of resistance tends to be a cross between an ungrounded system and a system with a low value of grounding resistance. With a high value of grounding resistance, the fault voltage may lead the fault current.

Figure 5. Sensitive ground fault settings for ungrounded, resonant-grounded, or high-resistance grounded systems.
The torque angle of the directional protection for this system can then be set somewhere around a capacitive 45° angle. For the Form 5 control, this is achieved by entering +45 into the MTA set point. For the Form 6 control with version 4.0 software and the Idea relay, this is achieved by entering -45 into the MTA set point and setting the Torque Angle Width to ‘Direction Forward’. For the Form 6 control with version 3.2 software, this setting is not available. Therefore, either an MTA setting of 0 and ‘Direction Forward’ or +90 and ‘Direction Reverse’ must be used to obtain a 0° MTA or a leading 90° MTA. See Figure 6 for example settings of the Form 5 and Form 6 controls and the Idea relay.

Note that the Form 5 directional SGF element uses zero sequence voltage (V0) for polarization (or torque angle reference). During a fault, the system voltage can collapse to a low value. The Voltage Threshold, required only on the Form 5 control for polarization, is typically set to 1–2% of rated voltage, depending on the level of noise in the system. The Form 6 control and the Idea relay use negative sequence voltage (V2) as polarization. Note also that if the MTA setting of the version 4.0 of the Form 6 control is set to a negative phase angle, that MTA may not be usable for directional phase or negative sequence directional protection at the same time as directional ground protection.

**Figure 6.**
Protectional ground settings for three-wire, high-resistance grounded systems.
Three-Wire Resonant Grounded:

**Description:** Three-wire resonant-grounded distribution systems are also known as Petersen Coil systems. In this system, no neutral wire is run with the three phase conductors and the transformer at the substation is grounded through a particular level of reactance. The reactance value is chosen to match a value of system capacitance such that the resulting fault yields a current in phase with the voltage reference. The very low resultant fault currents cause minimum damage and the fault arc often cannot maintain itself. This makes the potential for a restrike negligible. Usually, only the substation transformer is reactively grounded, so that ground currents must flow from the fault to the earth to reach the transformer.

**Ground Protection:** Since the transformer is directly grounded through a reactor, fault currents will be very low at the properly tuned values. Normal ground elements are often not able to detect these low levels of fault current. Therefore, an SGF element is required. It is usually set to a very low current value. See Figure 7 for example settings of the Form 5 and Form 6 controls and the Idea relay. Also, there often will be problems with faults from other feeders flowing in the opposite direction through the protected feeder to the substation. Called sympathetic current, this can cause false or sympathetic tripping with normal or sensitive ground protection. Sympathetic tripping can be reduced or eliminated by using directional ground protection.

![Figure 7](image-url)

**Figure 7.** Sensitive ground fault settings for ungrounded, resonant-grounded, or high-resistance grounded systems.
**Directional Ground Protection:** The direct link to ground used in a resonant-grounded distribution system is a planned inductance to give a fault that is in phase with the voltage. However, it is also possible for fault current to flow from other systems, called sympathetic current, which will have a differing phase angle from the tuned fault current. Sympathetic currents are generally quite out of phase with the reference voltage of that system, also called reverse direction. When the directional SGF element is set to the forward direction, it will trip for faults only on that feeder and ignore the reverse current from faults on other feeders.

Therefore, the directional ground elements can be set with an MTA of zero degrees of current with respect to the reference voltage. This will then react to actual faults on that system while disregarding currents from another system and allow the ground protection to be set to a sensitive level without experiencing nuisance trips. See Figure 8 for examples of setting directional ground protection for the Form 5 and Form 6 controls and Idea relay. Note that the Form 5 directional SGF element uses zero sequence voltage (V0) for polarization (or torque angle reference). During a fault, the system voltage can collapse to a low value. The Voltage Threshold, required only on the Form 5 control for polarization, is typically set to 1–2% of rated voltage, depending on the level of noise in the system. The Form 6 control and the Idea relay use negative sequence voltage (V2) as polarization.

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**Figure 8.**
Protectional ground settings for three-wire, resonant-grounded systems.
Three-Wire Solidly Grounded Systems:

**Description:** In a three-wire solidly grounded system, the transformer is solidly grounded to earth at the substation only, with no neutral wire to connect the grounds of the distribution elements. Fault currents are very high near the substation but can be very low for high-impedance faults or faults that occur far from the substation.

**Ground Protection:** Three-wire solidly grounded systems don’t have neutral wires, so ground fault current must flow through the earth to the substation. There is wide disparity in the occurring fault levels, depending on the distance of the fault from the substation, the resistance of the earth, and of course the resistance of the fault itself. For this reason, the sensitive ground fault element is often used and set to a moderate level, so that all faults will be detected both near and far from the substation. The ground fault element could also be used and set to a minimum level. See Figure 9 for example settings for the Form 5 and Form 6 controls and the Idea relay.

**Directional Ground Protection:** The solidly grounded three-wire system has a direct path to ground at the substation. Ground fault current will be strongest between the fault and the substation, allowing normal ground elements to be effective in properly detecting faults. However, faults far from the substation can have small amounts of fault current, and an SGF element may be used for system protection to detect these faults. This will tend to make those protective elements susceptible to ground currents from a fault on one particular feeder, causing a trip condition on a neighboring feeder and an unnecessary outage. Sympathetic tripping, as this is called, can be
reduced or eliminated by using directional ground protection. When the directional SGF element is set to the forward direction, it will trip for faults only on that feeder and ignore the reverse current from faults on other feeders.

Because there is very little capacitance in the ground system, the fault current will normally reflect the inductance of the fault, so the MTA should be set to a 60° inductive angle with respect to the reference voltage. This will then react to actual faults on that system while disregarding currents from another system and allow the ground protection to be set to a sensitive level without experiencing nuisance trips.

See Figure 10 for examples of setting directional ground protection for the Form 5 and Form 6 controls and the Idea relay. For the Form 5 control, a 60° inductive setting is a -60 MTA, but for the Form 6 control and the Idea relay a 60° inductive setting is a +60 MTA. Note that the Form 5 directional SGF element uses zero sequence voltage (V0) for polarization (or torque angle reference). During a fault, the system voltage can collapse to a low value. The Voltage Threshold, required only on the Form 5 control for polarization, is typically set to 1–2% of rated voltage, depending on the level of noise in the system. The Form 6 control and the Idea relay use negative sequence voltage (V2) as polarization.
Potential Transformer Wiring for Three-Wire Distribution Systems

For normal ground or sensitive ground fault overcurrent protection, no potential transformers are necessary. The overcurrent element determines the overcurrent by summing the three current transformer readings. The resultant in a perfectly balanced system will be zero. However, if there is any ground current flowing, the three phase currents will be unbalanced and give a positive zero sequence reading. This is compared with the ground fault setting and the appropriate time–current curve to calculate whether to give a trip command. Single-phase connection of potential transformers (P.T.) given in Figures 11-14 may be used for power, though it is not necessary for overcurrent protection. The single-phase P.T. connection for the Form 6 control and the Idea relay is given in Figure 11 and the subsequent software settings in Figure 12. Phantom phase may be enabled to command the control to calculate the subsequent phase A and phase C voltages based on the actual input from phase B. Likewise the single-phase P.T. connection for the Form 5 control is given in Figure 13 and the subsequent software settings in Figure 14.

Directional ground protection must compare the fault current to a reference voltage, called polarization. The Form 6 control is polarized with negative sequence voltage (V2). The Idea relay is polarized with either V2 or with zero sequence voltage (V0). The Form 5 control, however, is polarized only with V0. In order to determine either V2 or V0 correctly, three potential transformers, one for each phase, must be used. Any other technique such as phantom phasing two of the phases will yield erroneous results, although there is a configuration using two potential transformers in an open delta that is acceptable for the Form 6 control and the Idea relay.

Figure 11.
Typical Form 6 single-phase P.T. wiring for three-wire distribution systems.

Figure 12.
Form 6 configuration settings for single-phase P.T. connection.
Ground Protection for Three-Wire Distribution Systems

Figure 13.
Typical Form 5 single-phase P.T. wiring for three-wire distribution systems.

Figure 14.
Form 5 configuration settings for single-phase P.T. connection.
The best connection of three potential transformers to the Form 6 control and the Idea relay is either a delta connection or an open delta connection. See Figures 15 and 16 for the appropriate connection scheme. A delta or open delta is preferred on a three-wire distribution system so that additional ground connections are not introduced to the system. The polarizing voltage for a delta configuration will be $V_2$, since $V_0$ polarizing requires a grounded wye configuration. Note that the control or relay must be wired for a delta connection (this is requested when ordering), and the software must

**Figure 15.**
Typical Form 6 delta P.T. wiring for three-wire distribution systems.

**Figure 16.**
Typical Form 6 open delta P.T. wiring for three-wire distribution systems.
be set as shown in Figure 17. If a grounded wye configuration is desired for either the Form 6 control or the Idea relay, this may be connected according to Figure 18. The polarizing voltage may be V0 or V2 in this case. Note that the control or relay must be wired for a grounded wye connection (this is requested when ordering), and the software must be set as shown in Figure 17.

Figure 17.
Form 6 configuration settings for delta- and wye-connected potential transformers.

Figure 18.
Typical Form 6 grounded wye P.T. wiring for three-wire distribution systems.
The Form 5 control, however, uses zero sequence voltage (V0) for polarization and so must have three potential transformers connected in a grounded wye configuration. This can be done in one of two ways. Since the control is being used on a three-wire system, it may be desirable to have a delta-connected primary to prevent grounding the system; see Figure 19. Note that this complicates setting the software because it must accommodate both a phase shift and a magnitude adjustment; the software settings are pictured in Figure 20. If the system can support a grounded wye primary, then the transformer connection is as shown in Figure 21. The associated software settings are then much simpler; see Figure 22.

**Figure 19.**
Typical Form 5 three P.T. wiring for three-wire distribution systems.

The Form 5 control, however, uses zero sequence voltage (V0) for polarization and so must have three potential transformers connected in a grounded wye configuration. This can be done in one of two ways. Since the control is being used on a three-wire system, it may be desirable to have a delta-connected primary to prevent grounding the system; see Figure 19. Note that this complicates setting the software because it must accommodate both a phase shift and a magnitude adjustment; the software settings are pictured in Figure 20. If the system can support a grounded wye primary, then the transformer connection is as shown in Figure 21. The associated software settings are then much simpler; see Figure 22.

**Figure 20.**
Form 5 configuration settings for delta primary/wye secondary P.T. connection.
Conclusion:

The Form 5 and Form 6 controls and the Idea relay have powerful settings for ground directional protection. How those elements are set in a three-wire system depends upon whether that system is ungrounded, high-resistance grounded, low-resistance grounded, reactance grounded, or solidly grounded. The proper settings will allow those elements to properly protect the applied system without causing unwanted outages for faults upstream or on different feeders and yet have the necessary sensitivity to protect the desired portion of the system. This paper has described some guidelines and conventions for making these settings. Appropriate use of these protection elements will lead to effective protection of the various three-wire distribution systems.