

TechTopics No. 98

Ground protection in metal-clad switchgear - ground sensor current transformers vs. residual connection of current transformers

Providing protection for ground faults is a well-established need, but some users are still confused about the proper protection schemes to be used for various system configurations. This issue of TechTopics discusses the two most common methods of sensing ground fault current and the system conditions for which each is appropriate.

Figure 1 on page 2 shows ground sensing by means of a toroidal (donut) ground sensor current transformer (CT) that encircles the three-phase conductors and measures zero-sequence (ground) current directly.

Figure 2 on page 2 shows sensing of ground current by means of an overcurrent relay located in the common return conductor of the CT secondary current. The scheme in Figure 2 is appropriate for solidly grounded power systems, but not well suited for low-resistance grounded systems. The scheme in Figure 1 is the reverse – it is not well suited for use on solidly grounded systems but is well suited for use on low-resistance grounded systems.

Let's look at each scheme.

Zero-sequence current sensing (Figure 1)

The scheme in Figure 1 is often called zero-sequence sensing and sometimes, direct sensing or core balance. The CT encircles the three-phase conductors (and neutral, if the circuit is four wire). When a ground fault occurs, the ground current (a zero-sequence current) in each of the three phases (and the neutral) is additive in the primary circuit, which means that the CT will measure ground current directly, and without influence of differences in the phase CTs.

In order to properly sense the ground current, the user's primary cables have to be installed properly.

As discussed in TechTopics No. 50 - Ground sensor current transformer cable routing, the shield wires of the primary cables must be carried back through the opening in the CT and grounded on the load side of the CT. If grounded on the circuit breaker side of the ground sensor CT, the ground current will not be monitored correctly, as the zero-sequence components of the current passing through the phase conductors will be offset by the zero-sequence ground current returning through the cable shields.

Figure 3 on page 2 shows the method of cable routing. This figure also appears in TechTopics No. 50 - Ground sensor current transformer cable routing.

Since the zero-sequence CT does not have to be sized to carry normal phase current, the ratio of the zero-sequence CT can be much lower than the ratio of the phase CTs. The most common ratio for the zero-sequence CT is 50:5, although a higher ratio (such as 100:5) is sometimes used. This is a major benefit of using a zero-sequence ground-sensor CT, as it allows ground protection to be significantly more sensitive than phase protection.

However, to take advantage of this system, ground current must be limited to lower values than phase current. In low-resistance grounded applications, the ground current is typically limited to 400 A by a neutral ground resistor. Sometimes, higher values of current are possible, but 400 A is more common than higher values. The neutral ground resistor is almost always a limited-time resistor, usually 10 s but occasionally, 60 s.

What is the rationale for use of a neutral ground resistor and a limited time duration? This subject is beyond the scope of this issue of TechTopics, but a brief overview will suffice.

Figure 1: Direct ground-current sensing

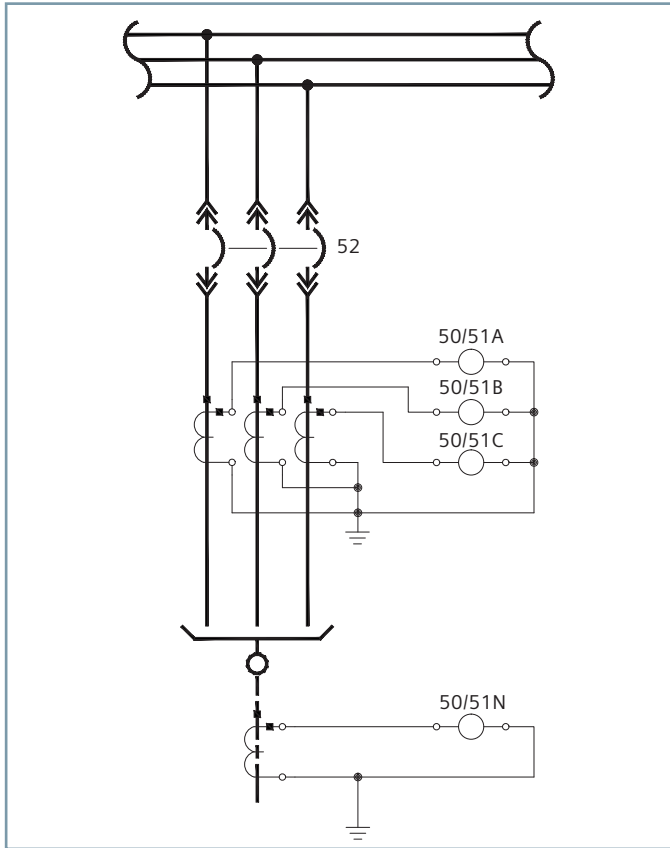


Figure 2: Residual ground-current sensing

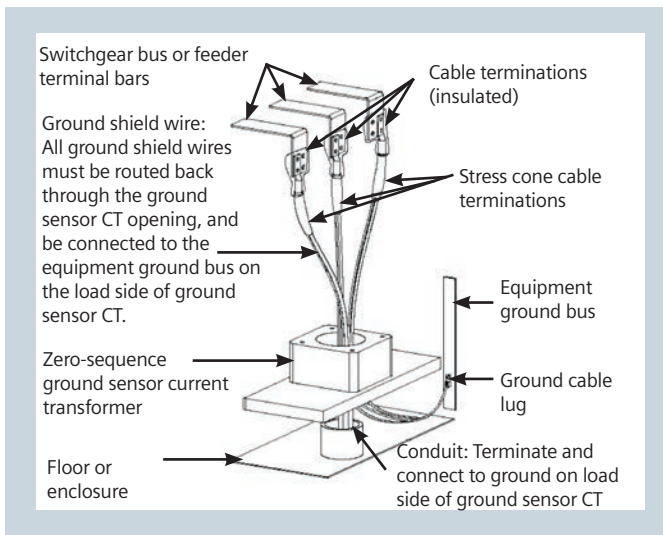
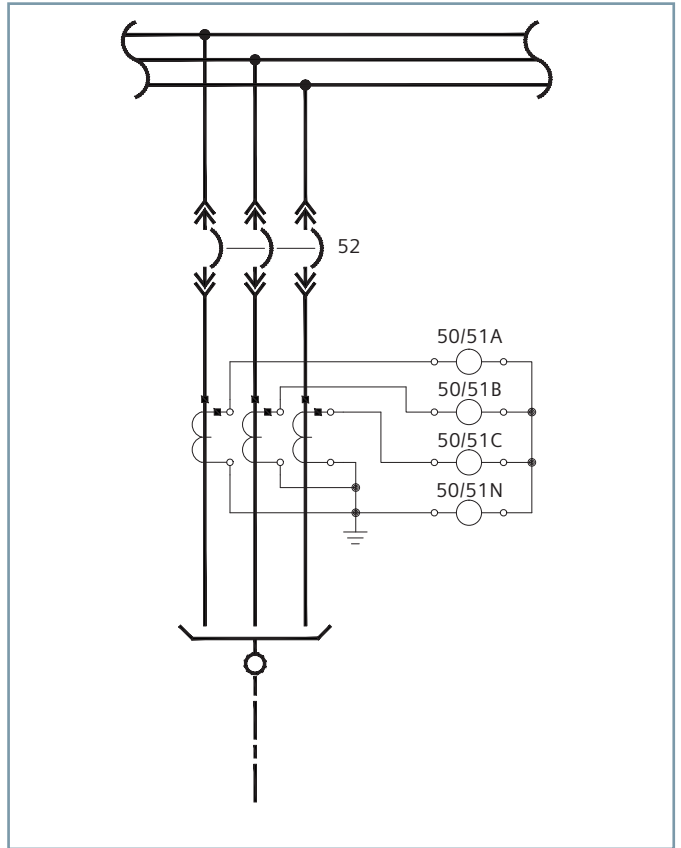


Figure 3: Correct cable installation with zero-sequence ground current transformers

The objective of using a low-resistance grounding scheme is to allow better protection of motors, and particularly to protect machines in such a way that, in the event of a ground fault inside the machine, the likelihood that the machine can be repaired (rather than replaced) is increased.

Motors are typically manufactured with the windings in grounded-wye. If a ground fault occurs in the machine windings, the amount of current that can flow in the fault will be related to the electrical “distance” of the ground location in respect to the grounded neutral point. If a ground fault occurs close to the line terminals of the motor, say 10 percent of the distance into the winding, there will only be 10 percent of the winding resistance in the path of the fault, and the fault current will be as high as it can be, limited by the neutral ground resistor and the portion of the machine winding from the location of the fault and the neutral point. If the ground resistor has a rating of 400 A, then a fault 10 percent of the way into the winding will allow 360 A of ground current to flow. If the fault location is moved to 50 percent into the winding, the fault current will be limited to 200 A. If the fault location is moved to 90 percent into the winding (close to the neutral point), the fault current will be limited to about 40 A.

The zero-sequence current transformer scheme can sense ground fault currents to this level, and thus, this scheme can protect up to about 90 percent of a machine’s winding length. It is not of great consequence that the system does not protect 100 percent of the winding, as the “unprotected” portion of the winding is near the neutral of the machine, where the voltage stress on the windings is lowest.

In this system, ground-fault current is limited to a relatively low value, and the time duration is also limited to a short-time period (based on the time rating of the neutral ground resistor), usually 10 s. This is very beneficial, since limiting current to low levels and limiting time to short durations decreases the amount of damage that will occur to the magnetic-core steel of the machine. If the magnetic-core steel is “burned” by excessive current and/or excessive time, the machine cannot be repaired except by replacing core steel, typically not a practical option. Thus, if the core steel is burned by a ground fault, the machine usually has to be replaced, rather than repaired.

Why can the zero-sequence or core-balance scheme not be used on solidly grounded systems? For this question, the CT accuracy ratings need to be reviewed.

This discussion will be very crude, rather than mathematically precise, to explain the issue as simply as possible.

Figure 4 shows a secondary excitation curve for a common zero-sequence CT.

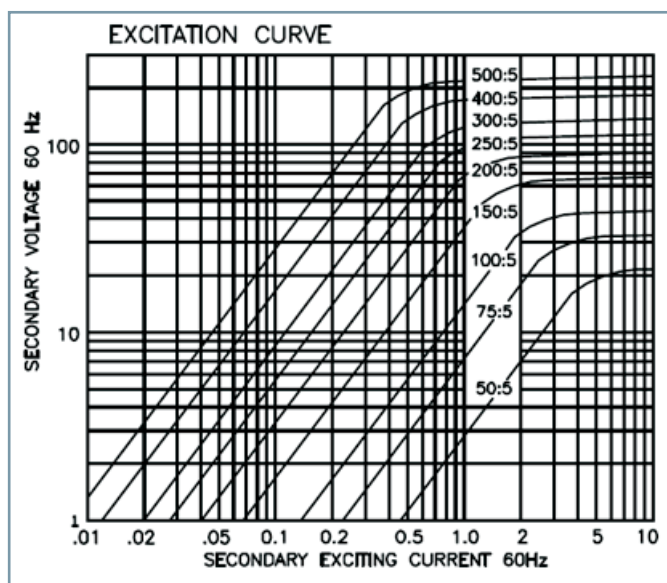


Figure 4: Secondary excitation curve for common zero-sequence CT

A secondary excitation curve is used to calculate the accuracy of a toroidal or window-type CT, which has an accuracy designated with a “C” classification. The method of calculation is directly related to the definition of accuracy classifications in IEEE Std. C57.13, which stipulates that the number following the C in the accuracy is the voltage that the CT can support in the CT secondary while not exceeding 10 percent accuracy error while carrying 20 times rated primary current. Conveniently, 20 times rated current (5 A for a CT with 5 A secondary winding), based on the secondary values, is $20 \times 5 = 100$ A, and 10 percent error would mean 10 A secondary excitation current.

So, a 50:5 ground sensor CT, as above, would support about 21 V at 20 times rated current with an error of 10 percent. The voltage “lost” in the CT secondary winding must be subtracted, in this case about 1.3 V, so the actual voltage supported on the connected load would be about 19.5 V. Thus, if more than 19.5 V were required to support the connected secondary burden, the CT would be pushed farther along (to the right) the secondary excitation curve, increasing the degree of saturation. The resulting accuracy would be considerably greater than 10 percent error.

Calculating on an extremely conservative basis, assume about 40 feet of wire in the CT secondary circuit from the CT location in the rear of the equipment, through the switchgear structure to the front of the switchgear, and then across the hinge loop to the protective relay on the front door, and return, and assume the typical AWG #14 wire, the resistance of the secondary wire would be about 0.107 ohms. Modern electronic relays have very low burden – let us use a very low value of 0.05 ohms for our purposes. The total resistance of the secondary circuit is thus 0.157 ohms. If the voltage across the CT is 19.5 volts (for the transformer above), this corresponds to 124 A in the secondary circuit. 124 A is above 20 times rated secondary current, and the required secondary voltage is at the upper limits of the CT secondary excitation curve for 10 percent error. Thus, the conclusion can be drawn that the CT is well into saturation.

A word of caution – this calculation is extremely crude so as to be as simple as possible. A theoretically correct calculation would have to use vector summation and the impedance with both resistive and reactive components. While the theoretically accurate calculation would not yield such high levels of saturation, that is not necessary for these purposes.

The example makes it clear that with zero-sequence ground sensing, the ground fault current must be limited using low-resistance grounding, such that the zero-sequence current transformer is not required to carry currents that are high enough to drive the CT into saturation. In the example, with 0.157 ohms secondary burden, with 400 A flowing in the primary circuit (40 A in the secondary circuit), the voltage across the CT would only be a bit over 6 V, and the secondary excitation current only about 2 A, less than 5 percent error.

Turn now to the residual ground sensing scheme as shown in Figure 2.

Residual ground-sensing scheme (Figure 2)

In the residual scheme, the ground fault current is sensed by means of an overcurrent relay in the common return conductor of the phase CT secondary circuit. This scheme is not commonly referred to as a zero-sequence sensing scheme, even though it is really a zero-sequence sensing scheme. As noted in the discussion of the zero-sequence (direct) ground scheme, ground currents are zero sequence currents, and zero sequence currents are additive in the neutral. Thus, the residual scheme is a true zero-sequence sensing method even though is rarely referred to this way.

Since the CTs must have a ratio high enough to carry normal phase current without overheating, the scheme is much less sensitive to ground current than the zero-sequence or core-balance scheme of Figure 1. Thus, the residual sensing scheme cannot provide sensitive ground sensing to protect machine windings.

The ratio of the three-phase CTs must be equal, and the ground current sensed will have some error introduced by the difference between the three CTs, but this is seldom an issue.

The residual scheme is applicable for use in solidly grounded systems, where the ground fault current is not limited to low values. In the residual scheme, CT saturation is only an issue to the same extent that it would be an issue for the phase current transformers. If the phase CTs are adequate for phase current sensing under short-circuit conditions, then they are also adequate for ground fault current sensing using the residual scheme.

Summary

Not addressed are other forms of system arrangements, notably, the ungrounded system and the high-resistance grounding system.

In the ungrounded system, ground current is limited to the system capacitive charging current of the cables, commonly called $3 I_0$, where the capacitive charging current of each phase is typically 1-2 A and total ground current typically 4-5 A. This current is too low to be sensed with current transformers, so a system using voltage transformers is needed.

Similarly, with the high-resistance grounding system, ground current is severely limited, often to 5-10 A, and the system is designed so that this level of ground current can exist indefinitely. This allows for time to locate the ground fault without having to immediately shut down the system. The ground current can be sensed directly at the ground resistor, or the ground condition can be detected by monitoring the voltage across the resistor. However, the determination of which of several feeders is faulted cannot be determined as simply. Typical high-resistance grounding schemes use a pulsing contactor to switch resistance values, resulting in a pulsing current on the faulted feeder, which can be detected with a clamp-on meter. Since this scheme does not use CTs on each feeder circuit, this scheme is also outside the scope of this issue of TechTopics.

The objective of this issue of TechTopics is to illustrate the proper application of the zero-sequence or core-balance scheme (Figure 1) and the residual scheme (Figure 2) for sensing ground fault current. The zero-sequence scheme is suitable for low-resistance grounded systems, while the residual scheme is suitable for solidly grounded systems.

It should be noted that the zero-sequence or core-balance scheme cannot be used for circuits involving metal-enclosed bus (bus duct) connections, or direct connections to power transformers. This is because the phase conductors are widely spaced, and a CT large enough to encircle the phase conductors would be excessively large. In addition to being too large, the secondary resistance of the CT itself would be much higher than for a normal ground sensor CT, reducing the accuracy of the CT to lower values. These situations occur most frequently with main circuit breakers, and fortunately, there is a convenient method to sense these ground currents, by installation of a CT in the connection of the neutral ground resistor to ground.

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