Critical power systems are designed to comply with stringent requirements for power availability and quality. In order to comply with these requirements, multiple power sources are tied together through various arrangements of circuit breakers. A simple example of such systems is the generator-utility transfer switch. Another example is parallel redundant UPS (uninterruptible power supply) equipment used in data centers. While connecting multiple sources of power improves redundancy and power availability, it complicates the design of the code-mandated ground fault protection for solidly grounded power systems.

Ground faults are typically caused by insulation deterioration due to aging. However, they can be caused by human error during equipment maintenance. Solid grounding provides a low impedance return path for ground fault currents. Consequently, the magnitude of the fault current can be very large, causing damage to equipment and producing hazards for personnel.

The purpose of ground fault protection is to trip the circuit protective devices quickly in order to minimize damage at the point of fault. However, sensitive ground fault protection is sometimes prone to nuisance tripping due to the way the system topology is laid out. For mission critical power systems, where continuity of service is of the essence, such nuisance trips must be minimized.

THE PRINCIPLES OF GROUND FAULT PROTECTION

A modern microprocessor-based low voltage circuit breaker (Figure 1) includes:

1. Fault sensing current transformers installed on three phases and the neutral (neutral sensor is only necessary for 4 wire power distribution).

2. An electronic device that converts the output of the current transformers to digital signals for the microprocessor trip unit.

3. The Microprocessor-based trip unit.

In figure 1, the arrows and the numbers indicate an arbitrary assignment of the instantaneous values of currents in the conductors. As it can be seen, under normal conditions, the sum of the currents in the three phases and the neutral is zero. When a ground fault exists, the sum of the three phase currents and the neutral equals the ground current. The circuit breaker trips in response to this ground current. Figure 1 describes the basic functionality of the “radial” ground fault system.

SYSTEM AND GROUNDING OPTIONS

Figure 2 shows a simple utility-generator automatic transfer. The two sources of power in figure 2 may be selective or they may be run in parallel. Parallel operation may be momentary or of extended duration. In the selective system mechanical or electrical interlocks are used to assure that only one of the two sources is connected to the load bus. In the parallel system, however, the power sources are synchronized and connected together. As it will be shown later, the connection method (selective versus parallel) has a significant impact on the functionality of the ground fault system.

The second important consideration is the location(s) where system neutrals are connected to ground. In figure 2 it is assumed that the neutral of each source is independently grounded. The alternative arrangement is to extend the neutral conductors into a common point in the switchgear and connect them.
to ground in one location. As it will be shown later, the method of grounding also impacts the functionality of the ground fault system.

DEVELOPING SYSTEM’S SPECIFICATIONS

Systems can be designed with specific arrangements of circuit breakers – for example a tie circuit breaker can be specified to be normally open or normally closed. However, operational requirements and human error can change these pre-defined conditions. Therefore, to insure safe operation of the electrical system at all times, the ground fault system must be designed so that it can operate correctly with any configuration of circuit breakers – open, closed, racked out, etc.

In facilities serving important loads dependent on power continuity, i.e. mission critical facilities, design of ground fault protection deserves special consideration. High reliability expectations combined with relatively more complex configurations and a desire to economize the system give us three fundamental design criteria, which form the basis for mission critical project specifications:

1. Any ground fault within the system shall trip only those circuit breakers that feed energy directly into the fault. The remainder of the system shall not be affected. In other words, the extent of the outage must be kept to a minimum number of circuit breakers that are required to isolate the fault. This is called “selectivity.”

2. The design should utilize the low voltage ground fault trip functions normally found on circuit breakers. Addition of costly differential relays external to the breakers should be avoided. Designs that incorporate circuit breaker status auxiliary contacts into the ground fault circuitry should be avoided as such systems can be easily defeated due to human error during maintenance.

3. The design shall work whether any circuit breaker is open, closed or racked out.

IS THE NEUTRAL CONDUCTOR NECESSARY?

When multiple sources of power are tied together, the response of the circuit in Figure 1 gets complicated. One major source of complication is the way system neutral conductors are used. In order to supply single phase 277 V loads such as fluorescent lighting, system designers sometimes extend neutral conductors throughout the power distribution system. Figure 3 illustrates such neutral conductor connection for a utility - generator transfer system.

With this arrangement of neutral conductors, a fault supplied by bus A will have multiple return paths to the source. For example, if the generator is not running, we would normally expect the ground current depicted in figure 3 to return through the neutral to ground bond of the utility transformer. However, as illustrated, a portion of this current may return through the neutral to ground bond of the generator, travel over the neutral bus and return to the utility source as neutral current.

This will compromise ground fault protection. Circuit breaker MA may not sense sufficient ground current to trip, while circuit breaker GA senses a ground current even if the generator is off. Also, during normal operation of the system on either the utility or generator source, neutral current may flow on the grounding electrode path. Therefore, some designers argue that the circuit depicted in figure 3 is a violation of the National Electrical Code (NEC) Article 250-6 due to the multiple ground connections employed. Article 250-6 states that no “objectionable current” shall flow over ground wires.

Local electrical inspectors may in fact interpret article 250-6 to disallow the connection shown in figure 3, but such interpretation is not universal. If we had utilized a single neutral to ground connection (figure 4)
we would still have a problem with ground fault protection if basic radial ground fault protection is used. If the generator is on and the utility source is off, the fault current will return to the generator as neutral current – defeating the radial ground fault system on the generator.

The problem shown in figures 3 and 4 gets much more complicated if we connect more than two sources together (with or without tie circuit breakers). Although there is no industry standard in this area, switchgear manufacturers have solved these problems using the “modified differential” design of ground fault protection. This may necessitate employing extra ground sensors and special connection of the sensors and circuit breaker trip units.

All this added complexity must be weighed against the need for extending the neutrals out of the main switchgear to serve small phase-to-neutral loads. If 277 V power is needed within the facility, a stable neutral can be easily derived downstream using an isolation transformer. Eliminating the neutral conductors from large portions of the electrical system will save significant amounts of copper, which will help defer the cost of an isolation transformer for 277 V loads. In many projects it has been proven to reduce costs.

AND THERE IS NO PANACEA

Figure 5 shows the system of figures 3 and 4, but with neutral conductors removed and each source properly grounded. The system in figure 5 will respond correctly to ground fault currents and is perfectly suitable for a selective system where the two sources will not be connected to the load bus at the same time. But spurious tripping of circuit breakers due to circulating currents can occur if the two sources are run in parallel and the ground fault protection on the circuit breakers is set too sensitive.

Circulating currents sometimes exist when multiple sources of power are tied together. They appear due to differences in the magnitudes or phase angles of the source voltages, a condition that exists during synchronization and paralleling of sources. They may also exist due to harmonics. Third harmonic currents have been known to circulate between generator and utility sources where the “pitch” of the generator windings is such that third harmonic voltages are produced.

Figure 5 illustrates the circulating current. Ground fault protection of both circuit breakers MA and GA will interpret this current as ground fault and may trip if the ground fault relay is set low. Even though setting the ground fault relay at the maximum code allowed level (1200 amperes and 0.5 seconds delay) will typically prevent nuisance trips of this sort, a question may arise as to whether this practice provides optimum protection.

Therefore, in order to optimize the protection system, the simple radial ground fault protection may not be the best choice for parallel power sources. The problem of circulating currents can also be solved by employing a modified differential system. For example, the circulating current problem depicted in Figure 5 can be corrected by tying the ground fault sensors together as shown in figure 6. Working many scenarios of circulating currents and ground faults will prove that the circuit shown in figure 6 is workable for any (selective or parallel) system.

WILL 4-POLE CIRCUIT BREAKERS SOLVE THE PROBLEM?

Four-pole circuit breakers (or other devices that switch the neutral with the phases) are commonly used in transfer mechanisms to allow the two separately grounded sources to have a common neutral. Four-pole breakers resolve the ground fault problem in selective source systems, but they do not resolve the ground fault design problem in paralleled sources. Figure 7 demonstrates a paralleled utility source and generator
system where both sources are grounded and tied through 4-pole breakers. If these sources were to run continuously in parallel, they could be considered in violation of the NEC. Circulating currents and neutral currents could both flow into and out of the ground connections at both sources. These currents would be “objectionable” under terms of the code.

However, the transfer mechanisms using 4-pole devices are not normally intended to operate continually with both sources in parallel. The transfers are of short duration, long enough only to transfer loads from one source to the other. This transfer duration can be as short as few cycles or as long as several minutes depending on the load control mechanism of the generator source.

It must be noted that 4-pole circuit breakers do not resolve the ground fault design problems mentioned above while the sources are paralleled. With the radial ground fault protection shown in figure 7, the circulating currents will be interpreted by the circuit breakers as fault current which could result in a nuisance trip during the closed transition of the transfer mechanism. In addition, a fault occurring during the closed transition, as shown in Figure 7, could partially flow over the neutral path. Therefore, either of the two circuit breakers may not respond to a bona fide ground fault. In order to correct this error, a new current sensor must be added on the neutral to ground bonds, and the connection of the existing current sensors must be changed to develop a modified differential scheme.

SIMPLICITY IMPROVES RELIABILITY

Four basic rules are derived from the above discussions, which may help in selecting the right system for critical power applications:

1. Where solid grounding is employed, ground fault protection design is significantly simplified if the neutral conductors from multiple systems are not tied together. Stable grounded neutral can be derived close to the 277 V loads where it is needed. Isolation transformers have been successfully employed in this application for many years.

2. Where the power sources are selective (not connected to the load simultaneously), the circuit in figure 5 provides accurate ground fault sensing and code compliance.

3. When multiple sources are run in parallel, the possibility of circulating currents and its effect on ground fault protection must be evaluated. Ground fault protection may malfunction due to circulating currents if radial ground fault protection is applied and the ground fault trip circuit is set too sensitive. Some switchgear manufacturers may employ custom-designed ground fault circuits (modified differential), which are impervious to circulating currents (figure 6).

4. Although 4-pole circuit breakers satisfy the code requirements for closed-transition transfer mechanisms, they do not fully resolve the ground fault protection issues. Additionally, significant cost penalty must be justified for their use.

In practice, a variety of system topologies exist which complicate ground fault protection. Designing an optimum system requires an understanding of the principles of grounding and ground fault relay application. Some equipment manufacturers employ special ground fault designs that provide reliable and economical solutions. This requires a special connection of sensors and circuit breaker ground fault trip units in a modified differential arrangement. Figure 6 provides a simple example of this approach.

No matter the system topology or the degree of complexity of the inter-connections, a modified differential system can be designed. However, such systems require special design expertise and an elaborate startup and commissioning in the field due to the complex wiring employed. Recognizing the
four basic principles stated above will simplify the process and will provide an economical, yet reliable power system.
Figure 1: Radial Ground Fault Protection Circuit. The numbers and arrows indicate an arbitrary assignment of instantaneous currents. The sum of these currents is always zero unless a ground fault exists.

Figure 2: A Two-Source System can be Run Selective or in Parallel. Sources are shown individually grounded.
Figure 3: Multiple Return Paths Cause Ground Fault Mis-operation. This arrangement may also be a violation of NEC article 250-6 as the neutral and ground currents share common paths – neutral conductor may be forced to carry the ground current and vice versa.

Figure 4: Single Point Grounding Does Not Solve Ground Fault Mis-operation Problem. Even though the ground current is still flowing on the neutral conductor, this is not a violation of the NEC article 250-6. However, radial ground fault protection is defeated.
Figure 5: Circulating Currents can Cause Ground Fault Nuisance Tripping Where Two or More Power Sources are Run in Parallel and the Trip Units are Set to be Sensitive. Note that even though the neutral conductor is not extended, there is a low impedance path for neutral current flow through the grounding system.

Figure 6: Properly Designed Ground Fault Protection for Parallel Sources Requires Special Connection of Sensors and Circuit Breaker Trip Units
Figure 7: 4-pole Circuit Breakers (Switched Neutral) will not Simplify the Ground Fault Protection Design where the Sources are Run in Parallel.