Coordinating Ground Fault Protection with Phase Overcurrent Protection

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It was a dark and stormy night… actually 6:37am on the West Coast on a rainy winter morning. The local brokerage agency had just started its trading day. Unfortunately, moisture in the conduit system of the parking lot lighting was about to hit cable insulation that had been damaged during installation. The resulting ground fault dumped the main circuit breaker supplying the entire office complex. The brokers lost the use of their computers and phones during the best rally in the past year. Although the ground fault protection complied with code requirements, it was only on the main, which resulted in an outage of the whole system, even though the fault was downstream of the feeder. This article will examine the possibility of achieving selectivity between ground fault devices and standard downstream phase overcurrent protection which is always included as part of the feeder protection package whether a ground fault function is provided or not.

Ground fault sensing is insensitive to normal phase currents, and its settings are typically lower than those of the phase protective devices. For example, a 4000A breaker could have a ground fault setting as low as 800A, well below the rating of many feeders on its same bus. The ground fault setting on a 1200A breaker can be as low as 240A. At these levels of fault current, a ground fault function could trip out in only tenths of a second, while the phase overcurrent protection might take tens of seconds. For this reason, applying ground fault protection to feeders as well as the main is an accepted way of ensuring selective operation for ground faults but it is too often omitted for fear of the possible impact on project cost, even though that may be minimal.

But is it really necessary to apply ground fault protection on all feeders to ensure selectivity? In many applications the answer is “yes.” However, there are some circumstances where the feeder’s phase overcurrent devices could provide adequate protection and, if set properly, can coordinate with the main’s ground fault function. For this to occur, the available ground fault current must exceed the pickup setting of the feeder instantaneous trip. In these situations, the feeder circuit breaker should trip instantaneously and clear the fault before the main ground fault device would operate. So knowing the magnitude of ground fault current available is important.

There is a range of arcing ground faults possible at each point in the power system. At the secondary of the serving transformer, the maximum ground fault current is approximately the same as the available current from a three-phase bolted fault. Further out towards the load, the available ground fault current is dependent on the zero sequence impedance of the feeder conductors and ground return path as well as the positive sequence impedances used to determine the three-phase bolted faults. For this reason, at remote locations the maximum ground fault current can be significantly lower than the three-phase bolted fault current. There is also a minimum value of sustainable arcing ground fault current. Arcing faults limit fault current even more because of the resistive characteristics of the arc. Empirical data from tests suggest that the minimum arcing single phase fault is approximately 38% of the bolted fault value on 480V systems. In subsequent time current curves and their accompanying discussion, the minimum sustainable arcing ground fault level will be referred to as “MAGF.”

If we apply this multiplier to the calculated bolted single phase fault, we can determine the minimum arcing fault for each location in a distribution system. The MAGF establishes the lower boundary of the range of damaging ground fault currents, while the value for bolted faults establishes the upper boundary. The evaluation of protective device selectivity and the protection they provide to the connected equipment when subjected to ground faults can be limited to this range of currents. While the characteristic curve of a ground fault device may be set well below the minimum arcing fault level, that portion of the curve can be ignored since an arcing fault cannot sustain itself at those lower currents.

To examine the ground fault protection provided by circuit breakers more closely, two systems were modeled. The first was a high current system that consisted of a 4000A, 480V three-phase four-wire service with an available fault current at the service entrance of 48,000A. The second was a 1200A, 480V service with an available fault current of 20,200A.

On the high current system, the 4000A main circuit breaker incorporated adjustable long-time, short-time, instantaneous and ground fault functions. The main service feeders were rated 2000A, 1200A, 600A and 150A. The feeders rated 1200A and greater were equipped with adjustable long-time, short-time and instantaneous protection, while the other feeders incorporated long-time and adjustable instantaneous protection only. The second system was modeled with the same devices as the first, but the main was rated 1200A and the feeder ratings didn't exceed 600A.

Each of the feeder breakers serves a main lug only panel. No branch breakers were considered since this study only investigated the performance of the protection at the first panel downstream of each feeder. In more complex systems, an evaluation similar to the one conducted here must be done for all 480V panels connected to the feeder.

Mathematical models of each system were created in order to determine the available ground fault currents at each location. In order to get an understanding of the effects of feeder length, two calculations were made for each model. One calculation assumed short conductor lengths of 30 feet from the feeder breaker to the downstream panel. The second modeled longer distances of 200 feet between the feeder breaker and the panel.

Maximum ground fault currents were calculated assuming a bolted fault condition on a single-line-to-ground fault. The equation for determining these faults is $3E/(Z_1 + Z_2 + Z_0 + 3Z_G)$. In industrial and commercial distribution systems, Z_2 is typically assumed to be the same value as Z_1. In actual installations the return path $(Z_0 + 3Z_G)$ is a combination of several parallel paths that may include equipment grounding conductors, conductor raceway (if metallic), and earth. It is not possible to calculate a figure that can determine an exact impedance for all these possible pathways. However, typical values for the return path based on raceway type and equipment grounding methods have been determined. GE publication GET-6533A, "Ground Fault Protection for Solidly Grounded Low Voltage Systems," provides these typical values. The values are given in the form of a ratio: $(Z_0+3Z_G)/Z_1$. The ratio allows the user to calculate the impedance of the return path (Z_0+3Z_G) from the positive sequence impedance Z_1 that is used for balanced load calculations. A ratio of four for $(Z_0+3Z_G)/Z_1$ was used in this evaluation, which is appropriate for raceways containing a full-sized internal grounding conductor. The minimum sustainable arcing ground fault (MAGF) was determined by multiplying the maximum ground fault current by 0.38.

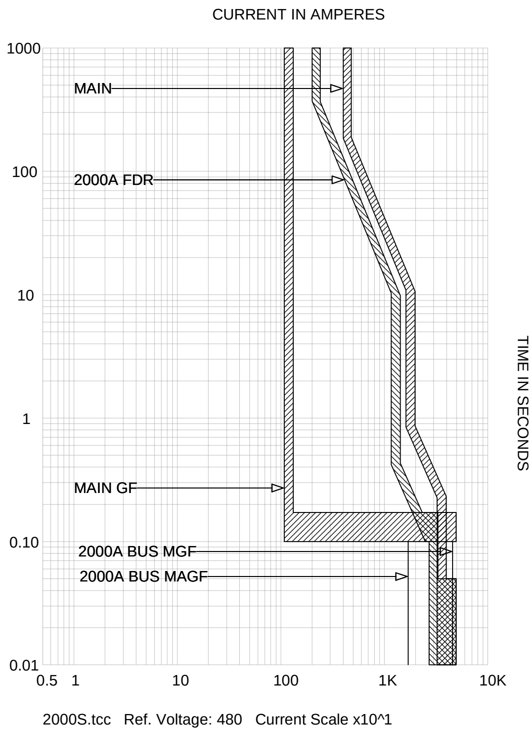

Figure 1 - A 2000A feeder supplying a short conductor.

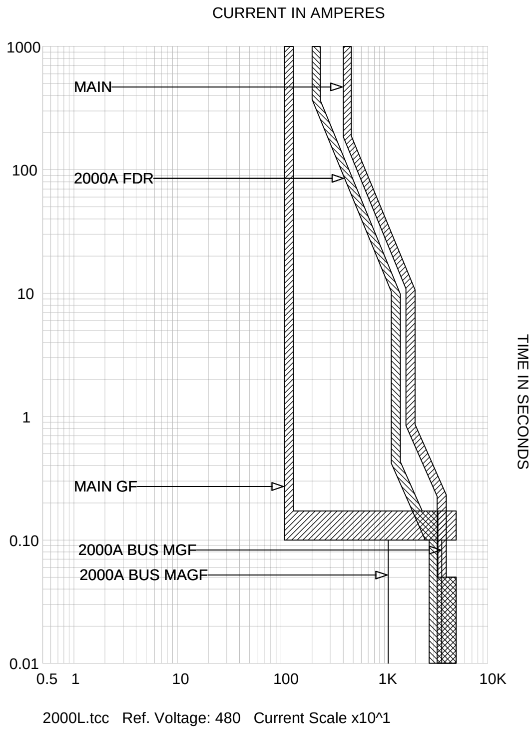

Figure 2 - A 2000A feeder supplying a long conductor.

Time current curves of circuit breakers were created so that the coordination of the phase overcurrent and ground fault protection could be evaluated. A graph was created for each feeder illustrating the protective device performance and ground fault currents for short conductor distances (30 feet) and long conductor distances (200 feet). The phase overcurrent characteristic of the feeder breaker was plotted. All adjustable instantaneous trips were set to their maximum levels in order to optimize coordination with downstream circuit breakers (not plotted). The magnitude of the maximum three phase bolted fault current at the downstream panel is indicated by a vertical benchmark line at the bottom of the graph labeled "(Bus name) MGF." The three-phase bolted fault was used as an upper limit to account for the possibility that $(Z_0+3Z_G)/Z_1$ might be a low ratio, approaching unity. A second benchmark line illustrates the MAGF or the lower limit of possible ground faults. These two benchmarks define the range of currents for which we will focus this evaluation. The main ground fault characteristic is plotted and extends to the level of the maximum ground fault current at the service. The main ground fault pickup was arbitrarily plotted at 1200A, which is the maximum setting allowed by code. While the pickup setting may have been lower, it wouldn't have made a significant difference to the results of this study.

The analysis results indicate that feeder phase protection rated 600A or less could coordinate with the main's ground fault device for ground faults occurring downstream of the feeder breaker. Let's look over a few time-current graphs to see how this happens.

The graph in Figure 1 shows the coordination of the 2000A feeder circuit breaker with the 4000A main. In this case, the feeder conductor is 30 feet long. The range of available ground fault current is shown by a pair of vertical benchmark lines at the bottom of the graph. "MAGF" indicates the panel's minimum arcing ground fault while "MGF" shows the maximum bolted ground fault. As noted previously we want to focus on the range of currents between the MAGF and MGF. The feeder instantaneous curve is shown at 10x. It would have to be adjusted to approximately 5x for selectivity with the main ground fault device to occur, Such a low feeder instantaneous setting could limit downstream motor inrush levels and compromise branch circuit coordination. As a result, two tier ground fault may need to be applied if full selectivity is required. Notice that there is a significant portion of the range of currents where the main ground fault might trip before the feeder breaker, beginning at the MAGF and continuing up to 32,600A where the feeder instantaneous will clear the fault.

Figure 2 shows the same collection of circuit breakers, but here the downstream equipment is separated from the main switchboard by 200 feet of cable. Not unexpectedly, the MAGF is much lower and increases the range of currents where miscoordination exists between the main ground fault and the feeder breakers. This range of currents starts at about 12,000A and continues to 33,000A.

The 1200A feeder performed better than the 2000A feeder. The best performance of the 1200A feeder was on a short feeder (see Fig 3), which still resulted in a small range of coordination uncertainty between about 16kA to-20kA. This is considered minimal and marginally acceptable. On the longer feeder (not pictured), the range of currents for which there was no coordination between the main ground fault and the feeder breaker phase settings extended from about 9,500A to 19,840A

Figure 4 illustrates coordination of the 600A feeder when applied on a short run of conductors. On this graph the main phase protective characteristic was omitted because we know that the 600A feeder settings are lower than those of the 2000A or 1200A settings and so the 600A feeder will coordinate with the main phase functions. The feeder instantaneous pickup is set to about 6,000A, which is well below the MAGF. The switchboard feeder breaker will isolate a panel ground fault before the main ground fault can initiate a trip.

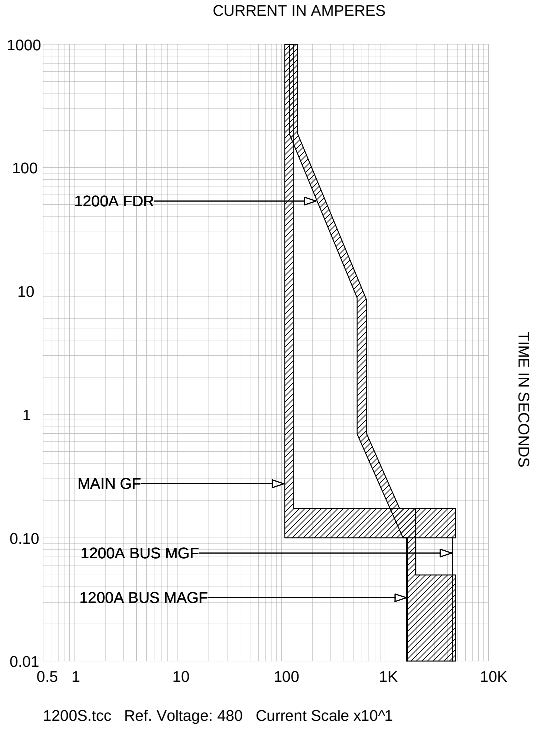

Figure 3 - A 1200A feeder supplying a short conductor.

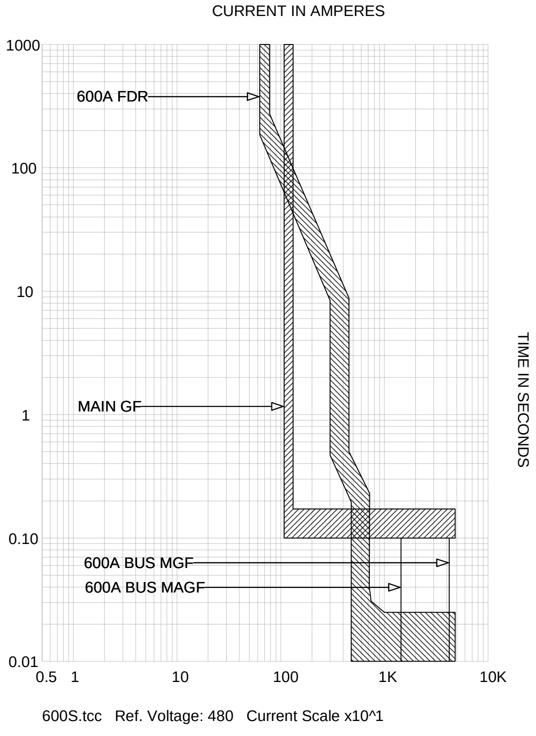

Figure 4 - A 600A feeder supplying a short conductor.

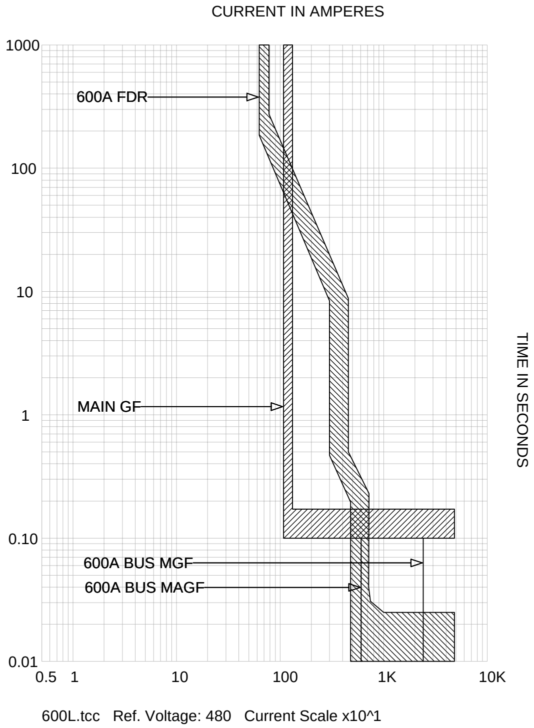

Figure 5 - A 600A feeder supplying a long conductor.

If the conductor distance on the 600A feeder is extended to 200 feet (Figure 5), the coordination is not as certain, but still very good. The MAGF falls within the tolerance band of the feeder instantaneous trip. The current range of miscoordination is very minimal from about 6,000A up to 7,200A. For the rest of the ground fault current range, which continues up to about 22,000A, the 600A feeder will coordinate with the main ground fault trip. To achieve full coordination the 600A instantaneous trip must be set at about 8x, but this could compromise selectivity with downstream circuit breakers.

The results for the 150A feeder are very similar to that of the 600A feeder. The feeder breaker coordinates with the main ground fault on short feeders (Fig 6) and becomes marginal when the feeder distance extends to 200 feet (Fig 7).

On more moderate current systems, the 600A feeder still performs well for shorter feeders, but not quite so well for extended length feeders. Figure 8 shows the coordination of devices on a 1200A service, with the largest feeder rated at 600A. The main phase overcurrent is displayed as well as the ground fault characteristic. This

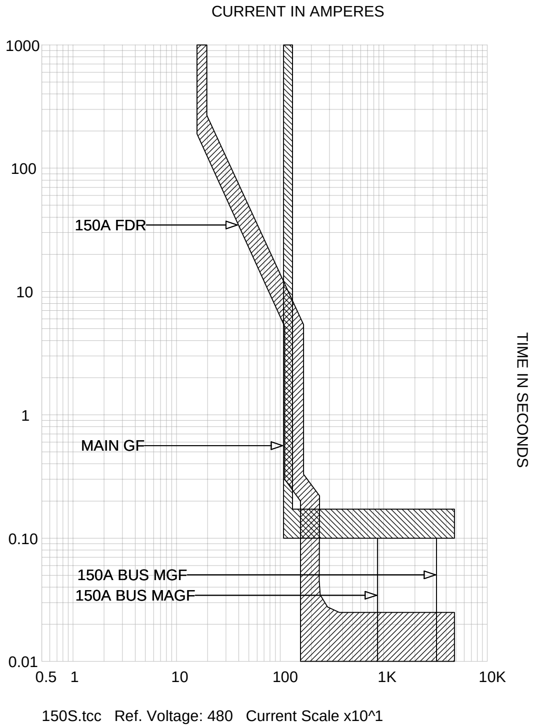

Figure 6 - A 150A feeder supplying a short conductor.

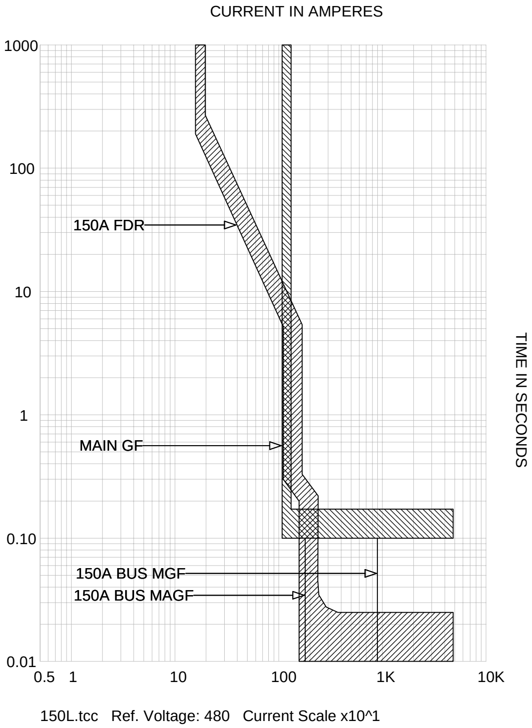

Figure 7 - A 150A feeder supplying a long conductor.

graph shows the range of ground fault currents when the 600A feeder is 200 feet long. The MAGF benchmark is lower than the minimum tolerance of the 600A feeder instantaneous trip. There can be no assured coordination between the main ground fault and the feeder breaker for ground faults that occur within a range from about 4,100A up to about 7,200A. Beyond that, up to the maximum ground fault current of about 16,000A, the feeder will coordinate with the main ground fault. For full coordination, the feeder's instantaneous trip needs to be set at about 5x, but again, understand that such settings may cause a reduction in coordination with downstream circuit breakers.

If the conductor distance of the 600A feeder is shortened to 30 feet, the MAGF increases to about 7,200A, which would align it with the maximum tolerance of the 600A feeder's instantaneous pickup. Therefore, coordination between 600A phase overcurrent feeders and the main ground fault trip is assured only when the conductor run is very short.

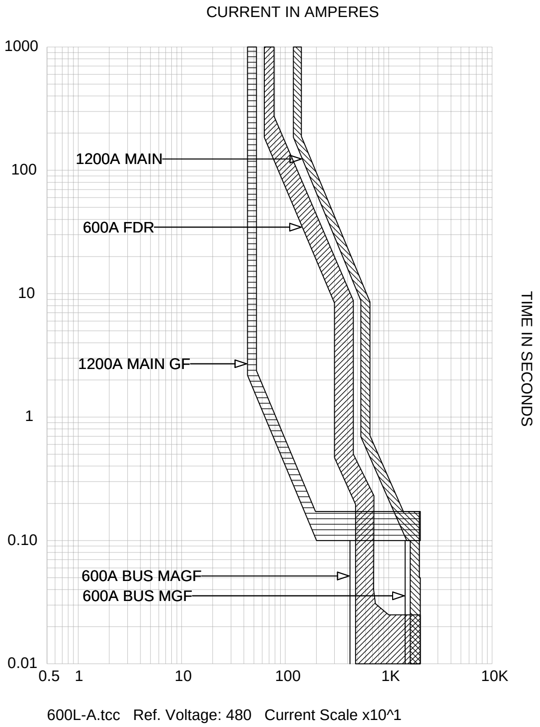

Figure 8 - A 600A feeder on a 1200A service.

Figures 9 and 10 illustrate the coordination of 150A feeders with the ground fault trip of the 1200A main. The characteristics are similar to those displayed of the 150A feeder on the 4000A system. Fig 9 illustrates the short conductor run, in which case the 150A feeder coordinates with the main ground

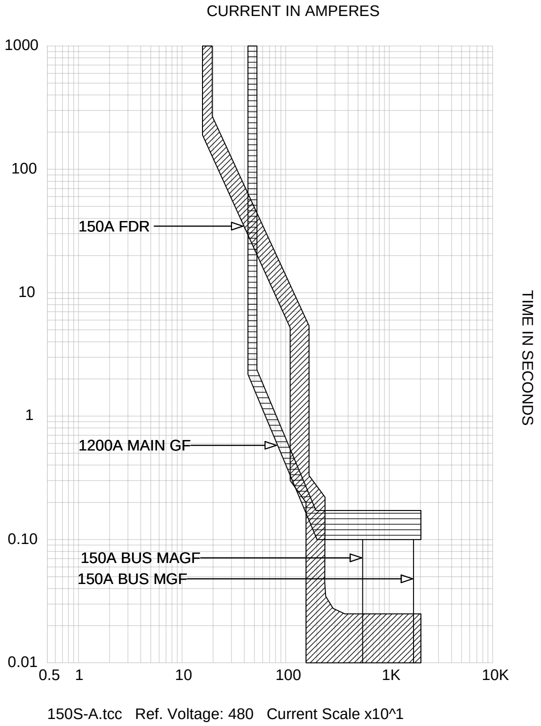

Figure 9 - A 150A feeder supplying a short conductor.

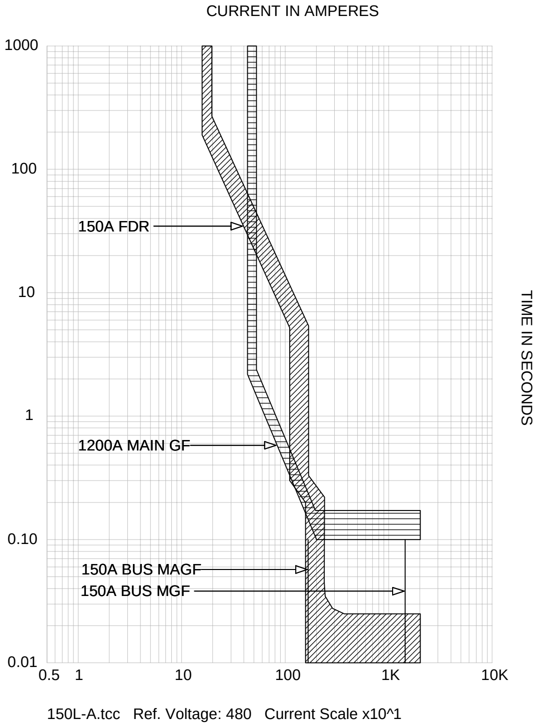

Figure 10 - A 150A feeder supplying a long conductor.

fault function for the full range of possible ground fault currents.

On longer feeders (Fig 10), the performance is marginal. The MAGF is just about equal to the minimum tolerance of the 150A feeder instantaneous trip. Coordination between the main ground fault and the feeder is not assured at ground fault currents beginning at about 1200A and continuing up to about 2400A. At higher ground fault currents, up to the maximum bolted fault current of about 14kA, the feeder breaker will coordinate with the main ground fault.

CONCLUSION

Selectivity is possible between upstream ground fault devices and downstream feeder phase protection in many cases and to varying degrees. Each case, however, must be evaluated on the basis of application and system needs. In general, coordination seems more likely when the feeder is relatively small compared to the upstream protective device. Most significantly, these results indicate that it is worthwhile to attempt such coordination. To accomplish this, appropriate ground fault current calculations should be performed in addition to the traditional short circuit calculations. Plotting the resulting ground fault levels on the time current graphs of a coordination study will help determine ground-to-phase coordination along with phase-to-phase coordination.

REFERENCES

"Ground-Fault Protection for Solidly Grounded Low-Voltage Systems," GE Publication No. GET-6533A, 1991.

IEEE Std 242-2001, "IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems," pg. 241-246