

Fault Indicators

Electrical Apparatus

320-05

Faulted Circuit Indicator Application Guide

Contents

General	1
Overview of Cooper Fault Indicators	2
Fault Indicator Reliability	3
System Conditions That Affect FCI Operation	3
Inrush Current	3
Cable Discharge	3
Proximity Effect	4
Backfeed Voltages and Currents	4
Temperature Compensation	5
Cable Preparation: URD	5
Simplify Fault Indicator Application	5
Fault Indicator Inrush Operation	6
Three-Phase System	6
Current Trace	7
Single-Phase System with Laterals	7

GENERAL

Fault indicators are devices which indicate the passage of fault current. When properly applied, they can reduce operating costs and reduce service interruptions by identifying the section of cable that has failed. At the same time, fault indicators can increase safety and reduce equipment damage by reducing the need for hazardous fault chasing procedures. To provide the greatest benefit, the fault indicator must indicate reliably when fault current passes through the cable to which the fault indicator is mounted. Misapplication or improper selection of the fault indicator can reduce reliability.

Figure 1 illustrates a typical looped underground distribution system. The underground cable is looped into and out of each transformer to the open point. Typically one fault indicator is placed on each incoming phase of the transformer. Figure 1 shows the fault indicator target position after a cable fault caused the tap fuse to operate. If the line is followed from the source, the fault would be located between the last tripped indicator and the first non-tripped (normal) indicator. Visual inspection of the fault indicator eliminates the need for trial and error sectionalizing of the system, thus reducing service restoration time.

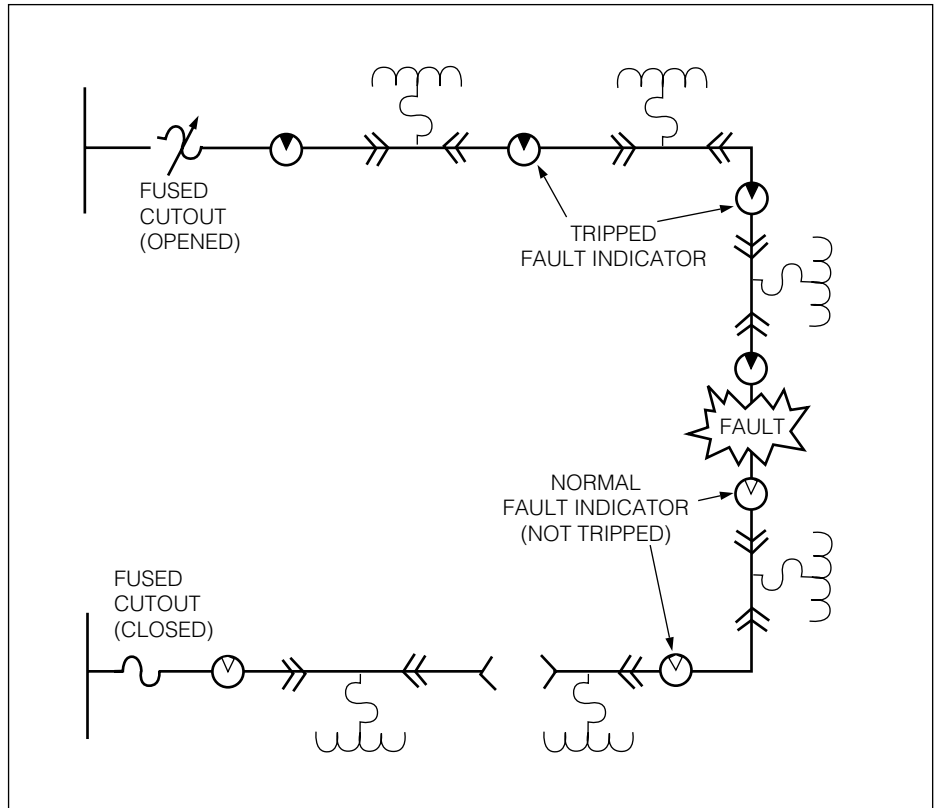


Figure 1. Typical looped underground system application.

Figure 2 illustrates a typical overhead application with a main sectionalizing fuse and unfused laterals. With a fault indicator on each lateral, the lateral on which the fault is located can easily be determined. This saves time in locating the fault, especially on lines located on terrain that makes visual inspection of the line difficult (i.e. swamps, wooded areas, mountain terrain).

Fault indicators can be installed on transformers, switchgear, sectionalizing cabinets, bushing terminators, overhead lines and underground cable. The quantity and location of the fault indicators should be sufficient to eliminate the need for the sectionalizing fault chasing method.

OVERVIEW OF COOPER FAULT INDICATORS

Cooper Power Systems offers a wide variety of fault indicators ranging from basic circuitry models in the Delayed Reset style to the more sophisticated circuitry of the Test Point Reset and Electrostatic Reset types. The Cooper Power Systems S.T.A.R. faulted circuit indicator product line offers five basic types of FCI's and each unit is tailored to be the most reliable for the intended application. Each type varies by reset method and the type of system it connects to.

All Cooper Power Systems S.T.A.R. faulted circuit indicators reset automatically upon restoration of system power or after a predetermined time period. Automatic resetting fault indicators sense either voltage or current to determine that power has been restored to the system. The units then reset to the normal position to eliminate the need for line personnel to manually reset the units. This saves time, money and makes the fault indication more reliable.

Table 1 shows an overview of the Cooper Power Systems faulted circuit indicator product line. It shows the fault indicator types based on reset method and lists the typical system application, physical mounting location and resetting requirements for each type.

Test Point Reset faulted circuit indicators are mounted to the test point of cable terminators (loadbreak elbows, deadbreak elbows, etc.). They are economical and simple to apply on underground distribution systems. Test Point Reset fault indicators require no special cable preparation in order to install and fit all major manufacturers voltage test points.

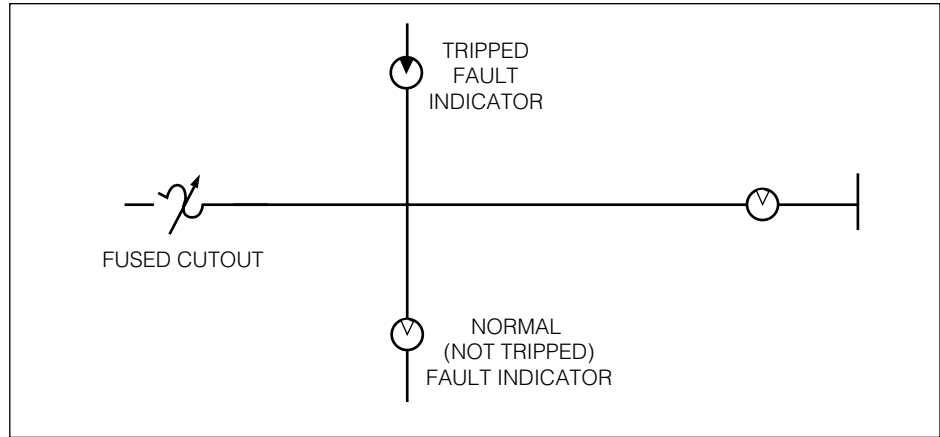


Figure 2.
Typical Overhead Application.

TABLE 1
Cooper Power Systems Faulted Circuit Indicator

Type Description	Typical System Application	Physical Mounting Location	Voltage/Current Requirements
Test Point Reset	Underground	On the test point of the connector	Min 5kV L-G
Low-Voltage Reset	Underground	On the URD shielded cable below the connector	A secondary voltage source (min. 105 volts)
Electrostatic Reset	Overhead	On bare or insulated non-shielded cable	Min. 6.9 kV L-G
Current Reset	Underground	On the URD shielded cable below the connector	Min. 2.4 A continuous
	and Overhead	and on bare or insulated non-shielded cable.	
Delayed Reset	Underground	On the URD shielded cable below the connector	None (Lithium Ion battery powered with timed reset)
	and Overhead	and on bare or insulated non-shielded cable	

Low Voltage Reset faulted circuit indicators are commonly used on underground systems where a voltage test point is not available on the cable terminator. It utilizes the secondary voltage provided by a distribution transformer to power the device. This fault indicator is ideal for single-phase padmount transformers where a secondary voltage source is readily available.

Electrostatic Reset faulted circuit indicators are powered and reset by the electrostatic field surrounding a bare or insulated, non-shielded conductor. These fault indicators are ideal for overhead distribution systems. A minimum line-to-ground voltage of 6.9 kV is sufficient to produce the potential gradient needed to power the device.

Current Reset faulted circuit indicators can be applied on systems where a voltage source is not readily available. A minimum continuous load current of 2.4 A must be present to power the fault indicator. Current reset fault indicators can be applied to either underground or overhead systems, provided the cable shield does not allow a return path for current to pass through the FCI sensor area.

Delayed Reset Faulted Circuit Indicators automatically reset back to the normal position when reset time has expired. They can also be reset with a manual testing/reset tool. This economical unit is ideally suitable for temporary use as a testing tool, since it does not contain all the standard features of the rest of the S.T.A.R. line. The unit is powered by a long lasting, lithium ion battery that provides the power to indicate the faulted conditions via a high intensity LED display.

FAULT INDICATOR RELIABILITY

All Cooper Power Systems faulted circuit indicators result in reliable operation when applied properly. To select a reliable fault indicator, one must consider the various operating conditions that can affect operation.

Reliability can have many different meanings. For some, fault indicator reliability means that the fault indicator operates every time a fault occurs on the distribution circuit. However, fault indicators may operate erroneously when not applied properly. A better definition of fault indicator reliability is that the faulted circuit indicators show proper indication each time they operate. This means that the units may only operate 95% of the time, but that the fault indicators will operate correctly each time they operate. Most operations personnel would agree that FCI misoperation causes more problems than FCI non-operation.

Cooper Power Systems has been providing fault indicators to the utility market for over 20 years. Experience shows that in order to achieve reliable indication, the proper fault indicator, with the appropriate features must be applied to the distribution system. In many cases, customers reporting inaccurate operation of fault indicators are applying a fault indicator that does not have the proper features for the application. Furthermore, the primary reason for the wrong fault indicator being used was the fact that the utility had such a large variety of units that line personnel became confused as to the proper FCI to use for a given application.

In 1991, Cooper Power Systems began a project to better understand what system variables can affect fault indicator operation. The goal of the study was to determine why fault indicators misoperate and how to correct the problems. In conjunction with a major customer of Cooper Power Systems, several underground distribution circuits, where known problems existed, were modeled. What was found provided a better understanding of what features should be standard on all faulted circuit indicators.

SYSTEM CONDITIONS THAT AFFECT FCI OPERATION

Inrush Current

Inrush currents can occur any time an electrical distribution system is energized. Inrush currents can exceed normal load currents by 12 to 60 times the normal load current. These higher than normal currents can falsely trip a faulted circuit indicator since fault indicators are typically peak sensing devices. Fortunately, system energization occurs in two distinct instances. The first being when the system has been without power for an extended period of time and the second being during a recloser operation.

If an automatic resetting faulted circuit indicator is being used, initial system energization will not affect the FCI indication, because the FCI will automatically reset to the normal position if the system remains energized.

The vast majority of FCI inrush operations are due to recloser operations. On most distribution systems, a reclosing device is almost always present somewhere on the system, either at the substation or further out on the feeder circuit. In the case of three-phase applications, recloser operation can cause tripping of fault indicators on phases not involved in the fault. The best method for dealing with inrush due to recloser operations is to inhibit the trip circuit following a momentary interruption of service. Cooper Power Systems fault indicators equipped with inrush restraint, will sense the momentary service interruption and keep the fault indicators in the normal position (see Fault Indicator Inrush Operation on page 6). If the reclose sequence is successful, the units will automatically reset and arm for the next operation. For simplicity of application, it is recommended that inrush restraint be specified on all faulted circuit indicators.

Cable Discharge

Cable discharge is a phenomenon that occurs at the instant of fault occurrence and manifests itself by tripping indicators beyond the fault. The 1991 system study showed that if a substantial length of cable exists beyond the fault, the charge on that cable can discharge to the fault. This cable discharge is usually of short duration, but can be of high enough magnitude to trip one or two indicators beyond the location of the fault, especially if the fault indicator has a relatively low trip rating.

Since the frequency of the cable discharge is in the several kilohertz range, it becomes possible to filter out the high frequency signals. This effectively eliminates the cable discharge as a source of FCI operation. The application of a low pass filter in the fault indicator sensing circuit will efficiently perform this function. The frequency of the low pass filter is set at a precise level that filters out the cable discharge, while allowing the fault indicator to indicate if a current limiting fuse is protecting the circuit.

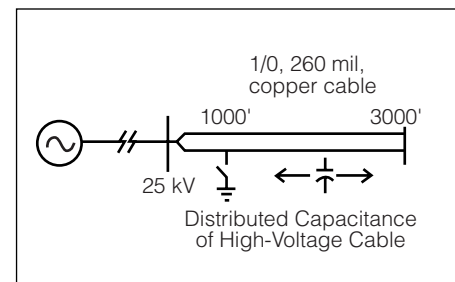


Figure 3.
A simplified 25 kV distribution cable system.

Figure 3 shows a simplified 25 kV distribution cable system with a fault having a variable amount of cable behind it. Assuming that the copper, 1/0 cable has an $L=196.3\mu\text{H}$ per foot and $C=59\text{nF}$ per foot the discharge frequency can be calculated:

$$f = 1/(2\pi\sqrt{LC})$$

If there is 1000' of cable behind the fault then $f = 46.77$ kHz.

Increasing the length of the cable behind the fault will not significantly change the peak outrush current that discharges into the fault. The frequency of the transient inrush current oscillation is however proportional to the length of the cable behind the fault. For example if 3000' were behind the fault the frequency would be reduced to 15.59 kHz.

Proximity Effect

Proximity effect is defined as the current from an adjacent cable affecting the operation of a fault indicator on the desired cable of operation. Proximity effect has two different modes in which it can affect fault indicator operation.

First, on multi-phase circuits, conductors of different phases can be in very close proximity to one another. This is especially true on underground applications. Due to the distance between the conductors, it becomes difficult for the fault indicator to distinguish between the magnetic field of the desired conductor and that of the adjacent conductor. Therefore, a fault on the adjacent conductor can cause the fault indicator on another cable to trip in error.

The second way proximity effect can influence cause fault indicator operation is when cables of the same phase are in close proximity to one another. For example, in a typical single-phase transformer application, incoming and outgoing primary cables are usually in close proximity to one another. In this case, the fault current would be traveling in one direction through the incoming cable and going in nearly the opposite direction through the outgoing cable. The current in the outgoing cable can then generate a magnetic field that effectively cancels the magnetic field generated in the incoming cable. This is especially true for low trip level fault indicators, because they are much more sensitive to the adjacent magnetic field.

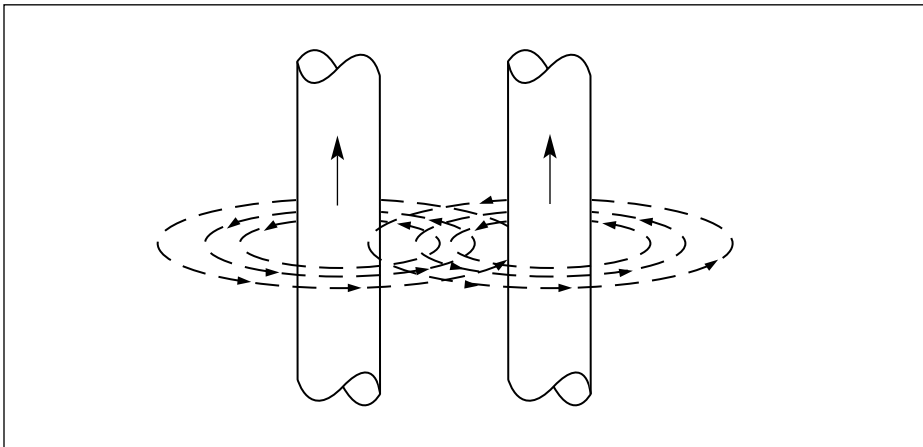


Figure 4.
Proximity effect illustration.

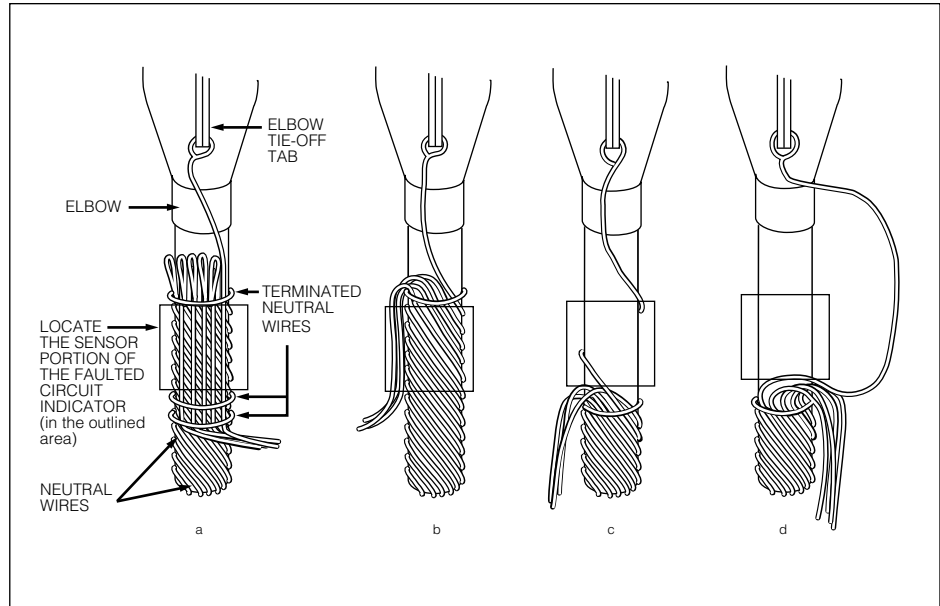


Figure 5.
Recommended methods of concentric neutral primary cable preparation.

Proximity effect can be eliminated in two ways. First, selecting a high trip rating can make the fault indicator less sensitive to adjacent phases. The second and most effective method for eliminating proximity effect is by the use of a current transformer (either open or closed core) to concentrate the flux from the desired phase and therefore reduce the sensitivity of the sensor to adjacent phases.

Backfeed Voltages and Currents

Automatic-resetting fault indicators that use either voltage or current to reset the unit when system power is restored can be affected by the system connection. Typically on systems where delta connections exist, single-phase sectionalizing can cause voltage or current backfeed which may cause tripped fault indicators to reset.

It is difficult to quantify the exact magnitude of the backfeed current without doing an in-depth system study. However, voltage backfeed can be quantified. Due to typical transformer connections, the maximum voltage backfeed that a fault indicator may see is 60% of the nominal system voltage.

This fact provides a means by which voltage backfeed can be eliminated as a cause of FCI resetting. A reset restraint circuit, with the threshold set above the 60% level will prevent the fault indicator from resetting in error.

Temperature Compensation

Temperature compensation is a feature that allows the fault indicators to provide a more accurate and reliable output between -40°C . and $+85^{\circ}\text{C}$.

S.T.A.R. fault indicators use a current transformer design to implement the low pass filter circuit and to minimize the affects of adjacent magnetic fields. These features provide a significant performance improvement over the use of a reed switch sensing circuit.

The copper coil of the current transformer changes resistance as the temperature varies, therefore, the output will also change due to variable temperature ranges. Cooper Power Systems designed and integrated a circuit that compensated for the temperature changes, therefore, providing an accurate output.

Cable Preparation: URD

Proper primary cable preparation is necessary for fault indicators to work reliably. The unit cannot be installed directly over the concentric neutral, because the unit monitors current. If the current in the neutral (return path) is high it could cancel the effects of the field from the fault current in the conductor. The net result could be less than the trip rating; therefore, the fault indicator would not trip. The line crew, upon investigation, would be misled by the false indication. The unit can, however, be mounted over the neutral if the neutral is double backed as shown in Figure 5 a and b. Doubling the neutral allows the FCI to detect the field from the fault current in the conductor because it eliminates a return path. Refer to Figure 5 for the recommended methods of concentric neutral primary cable preparation.

Fault indicators can be used on tape shield conductor or drain wire cable. If the cable shielding does not provide the return path for the indicator, the indicator can be installed directly to the cable. If the cable shielding provides the return path for the fault current, the indicator will not reliably detect a fault, as described above, and will require the use of a tape shield or a drain wire adapter. (An adapter must be installed approximately four inches below the elbow to allow ample space to mount the fault indicator on the cable.)

SIMPLIFY FAULT INDICATOR APPLICATION

Reliable fault indicator application can be achieved by selecting the proper faulted circuit indicator for the job, but in addition, the fault indicator must be applied properly in the field. The best method to assure proper field application is to make the application rules simple for field personnel.

Due to the characteristics of a typical distribution system, it is possible to achieve a high degree of fault indicator reliability while using just one or two trip ratings for the entire system. The application of the fault indicators then becomes a matter of applying the right fault indicator for the given system type.

In 1983, EPRI published a study called "Distribution Fault Current Analysis." This study showed typical fault current characteristics for a cross-section of distribution feeders throughout the United States. The results of the study showed that faults typically have less than two ohms of impedance. Furthermore, it showed that system fault calculations were relatively accurate when a zero fault impedance was used to calculate line-to-ground fault current magnitudes.

This information suggests that since the maximum line-to-ground fault current will flow to the fault, selecting a low trip rating on a fault indicator provides little added sensitivity over a fault indicator with a higher trip rating. As a matter of fact, due to phenomena like proximity effect, a lower trip rating can make the fault indicator less reliable than one with a higher rating. Therefore it makes sense to set the fault indicator trip rating based on the available fault current levels, not the load current level.

A better method for selecting a trip rating is to analyze the system parameters and select a trip rating based on a generalized system. For example, a typical 200 A underground system rarely carries more than 50 to 100 A, but is designed to carry a maximum of 200 A. While a trip rating just above the 100 A level could be selected, selecting a trip rating greater than the 200 A maximum continuous load current will allow the load current to vary anywhere in the acceptable current range. This trip setting can then be used for any 200 A underground distribution system. The only criteria that needs to be satisfied to make this philosophy work is that the fault indicator must respond faster than any protective device on the system.

As seen in Figure 6, the fault indicator will allow the load current to vary within the acceptable range without tripping. The FCI will trip when fault current reaches approximately 400 A, which is beyond any expected continuous load current, and less than the typical expected minimum fault current. And, because response time of the fault indicator is faster than protective equipment, the unit will indicate a faulted condition before any protective devices operate.

This philosophy will work for overhead distribution as well. A system that is protected by fused cutouts, can have fuse ratings from 1 A through 200 A. Since 200 A tin links can carry 150% rated load, the possible load currents could vary anywhere from a few amperes up to a maximum of 300 A. If a faulted circuit indicator with a trip rating of greater than 300 A is used, that trip rating could be used anywhere on the overhead system, provided the fault indicator is fast enough to beat out the fuse for any fault occurrence.

When using this application philosophy, one can also ignore any variations in the fault indicator trip rating due to changing cable dimensions, because as long as the trip rating is substantially larger than the maximum load current, the exact trip rating does not matter. The maximum line-to-ground fault current will flow to the fault, effectively tripping a fault indicator that is slightly higher in rating. This further allows the fault indicator to be applied generally to any system.

In general, a fault indicator applied to a 200 A URD loop should have a LOW trip rating (around 400 A) and a 600 A system should utilize a HIGH trip rating (around 800 A).

The last step to making the application of the faulted circuit indicator simpler is to make all the features that may be needed in any application standard on the fault indicator specified. For example, it is recommended that all fault indicators have inrush restraint. This means that this fault indicator can be applied anywhere on the system, even where a recloser is not being used. Therefore, the line personnel won't have to decide between a unit without inrush restraint and one with inrush restraint.

FAULT INDICATOR INRUSH OPERATION

The following is a description of how a system operates during inrush when fault indicators equipped with inrush restraint are applied.

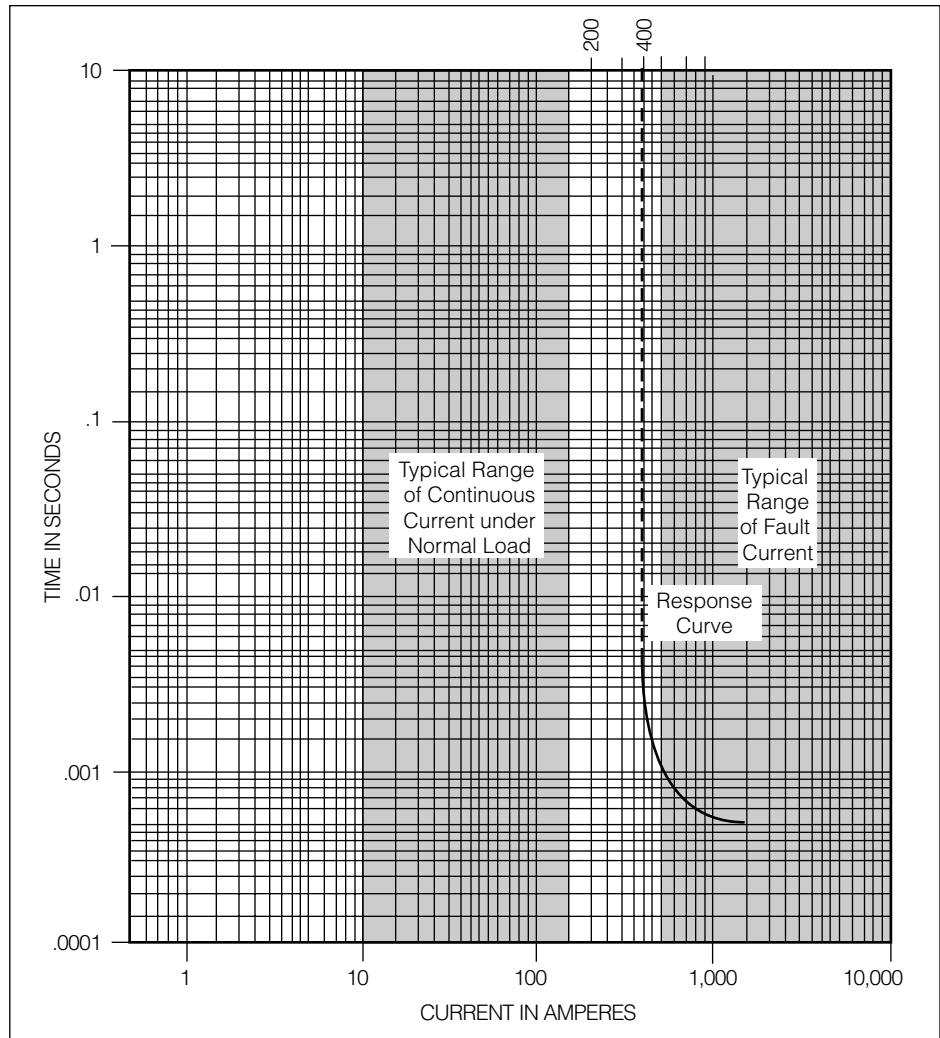


Figure 6. Low Voltage Reset faulted circuit indicator (Low trip rating) response curve as applied to a typical 200 A underground system.

Three-Phase System

(Refer to Figure 7)

- Fault occurs on Phase A. Fault current levels exceed trip rating of indicators and, thus, all indicators (#1 and #2) between recloser and fault trip.
- Recloser opens. Indicators, with inrush restraint, on Phase B and C detect loss of power. Deadtime is sufficient to fully discharge the trip capacitors.

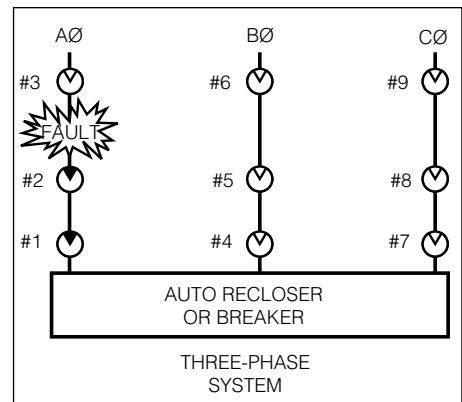


Figure 7. Typical Three-Phase Application of Fault Indicators with the Inrush Restraint Option.

- Recloser closes back in. Phase A sees fault current again. #1 and #2 indicators remain tripped while B and C phases experience inrush. Trip circuits for indicators on B and C phases have already been inhibited and, thus, will not trip.
- The recloser cycles until recloser lock-out occurs. The only tripped indicators are #1 and #2, thus, locating the fault between #2 and #3 on the A-phase.

Current Trace

(Refer to Figure 8)

- Time A - Normal Load Current All indicators in normal state.
- Time B - Fault occurs on Phase A (or A-leg of bifurcated feeder). All indicators on Phase A (or A-leg) between recloser and the fault trip.
- Time C - Recloser opens. Indicators with inrush restraint on B and C-phases (or B-leg and C-leg) detect loss of power.
- Time D - Deadtime exceeds time necessary to trigger inrush restraint circuitry. (i.e. 300 milliseconds, but in some cases 100 milliseconds). Indicators on B and C-phases (or B-leg and C-leg) inhibit their trip function in anticipation of inrush current.

Time E - Recloser closes back-in. A-phase (or A-leg) current rises to fault level. Previously tripped indicators on A-phase (or A-leg) remain tripped. B and C-phase (or B-leg and C-leg) indicators experience inrush, but do not respond due to disabled trip function at time D.

Time F - Recloser cycles until it locks open or until the fault is isolated by the operation of a fuse link or sectionalizer. The only tripped indicators are on A-phase (or A-leg) between the recloser and the fault.

Single-Phase System with Laterals

(Refer to Figure 9)

- Fault occurs on A-leg of bifurcated feeder. Fault current levels exceed trip rating of indicators and, thus, all indicators (#1 and #2) between recloser and fault trip.
- Recloser opens. Indicators, with inrush restraint, on B-leg detect loss of power. Deadtime is sufficient to fully discharge the trip capacitors.
- Recloser closes back in. A-leg sees fault current again. #1 and #2 indicators remain tripped while B-leg experiences inrush. Trip circuits for indicators in B-leg have already been inhibited and, thus, will not trip.

- The recloser cycles until recloser lock-out occurs. The only tripped indicators are #1 and #2, thus, locating the fault between #2 and #3 on the A-leg.

Current trace: Same as Figure 8.

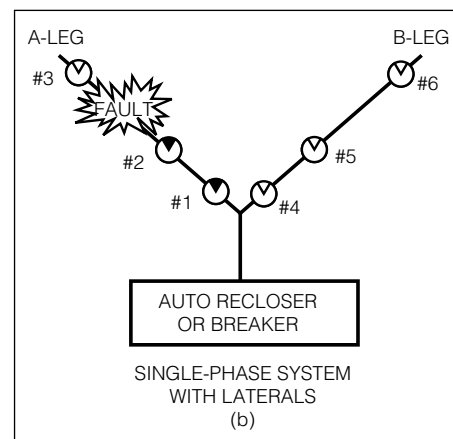


Figure 9. Typical Single-Phase Application of Fault Indicators with the Inrush Restraint Option.

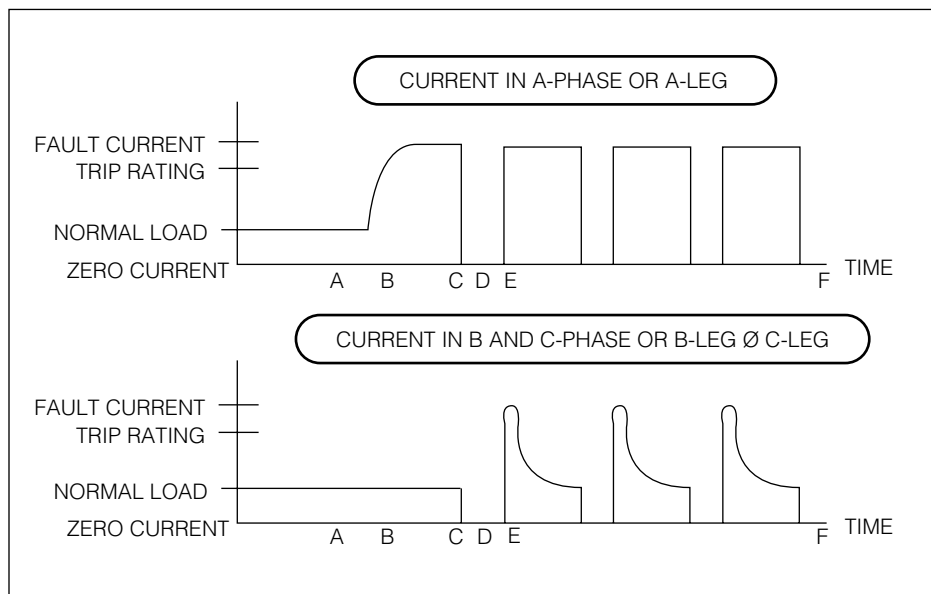


Figure 8. Current Trace for Three-Phase Application of Fault Indicators with the Inrush Restraint.



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