Summary Paper for C37.243 IEEE Guide for Application of Digital Line Current Differential Relays Using Digital Communication

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Contents

1. Overview

This paper is a summary of the C37.243 IEEE Guide for Application of Digital Line Current Differential Relays Using Digital Communication which has recently been developed in accordance with the following scope:

This guide presents practical line current differential schemes using digital communications. Operating principles, synchronization methods, channel requirements, current transformer (CT) requirements, external time reference requirements, backup considerations, testing considerations, and troubleshooting are included. It also provides specific guidelines for various application aspects including multi-terminal lines, series compensated lines, mutually coupled lines, line charging current, in-zone transformers and reactors, single-phase tripping and reclosing, as well as communications channel requirements.

2. Current Differential Line Protection Applications

Current differential line protection is a fundamentally different scheme than the directional comparison line protection schemes, which brings with it both advantages and disadvantages. The guide enumerates these comparisons in detail.

There are many advantages of current differential over other line protection schemes. Selectivity is the greatest advantage: line current differential schemes can achieve high-speed clearing for 100% of the protected zone, while not operating for out-of-zone faults. While backup protection for out-of-zone faults is not provided by the current differential principle itself, modern microprocessor relays provide means for these backup protection functions. In-depth discussion on current differential line protection versus distance protection schemes (step and pilot) is provided in the guide. Some additional advantages of current differential line protection described are: security under high-load conditions; simplified consideration of infeed for tapped loads; no potential transformers (PTs) and thus no loss-of-potential considerations; tripping not dependent on permissive or blocking signals; and immunity to current reversals.

All digital current differential line protection schemes require a digital communications channel between all protected terminals in order to operate properly. The requirements of the communications channel are a disadvantage of current differential line protection as compared to directional comparison schemes. The disadvantage of the communications channel requirements and other disadvantages, such as sectionalizing and tapped-load considerations, are described and discussed in the guide. The current differential line protection is also compared to directional and non-directional overcurrent schemes.

3. Current Differential Operating Methods

Digital line current differential relays need to accommodate possible relay measurement error and CT saturation to prevent false tripping, as do other current differential relays. They also need to accommodate the effects of the limitations of the communication system used to provide information about the currents at the remote end(s) of the line.

The current differential operating methods in this guide, which is focused on digital line current differential relays using digital communications, are grouped around three measuring principles: percentage differential, charge comparison, and alpha plane.

Percentage differential relays traditionally use a bias or restraint current based on the absolute value of one or more measured currents to restrain differential tripping. The operating characteristic of a percentage differential relay may be represented on a plot of operating current versus restraint current.

An example of a dual slope percentage differential characteristic is provided in the guide. It includes a minimum pickup level for the operating current, a sloped small current region to accommodate errors which are proportional to current such as CT and relay measuring errors, and a large current region to accommodate errors which increase more rapidly than current, such as due to CT saturation. Figure 1 shows the dual slope restraint characteristic.
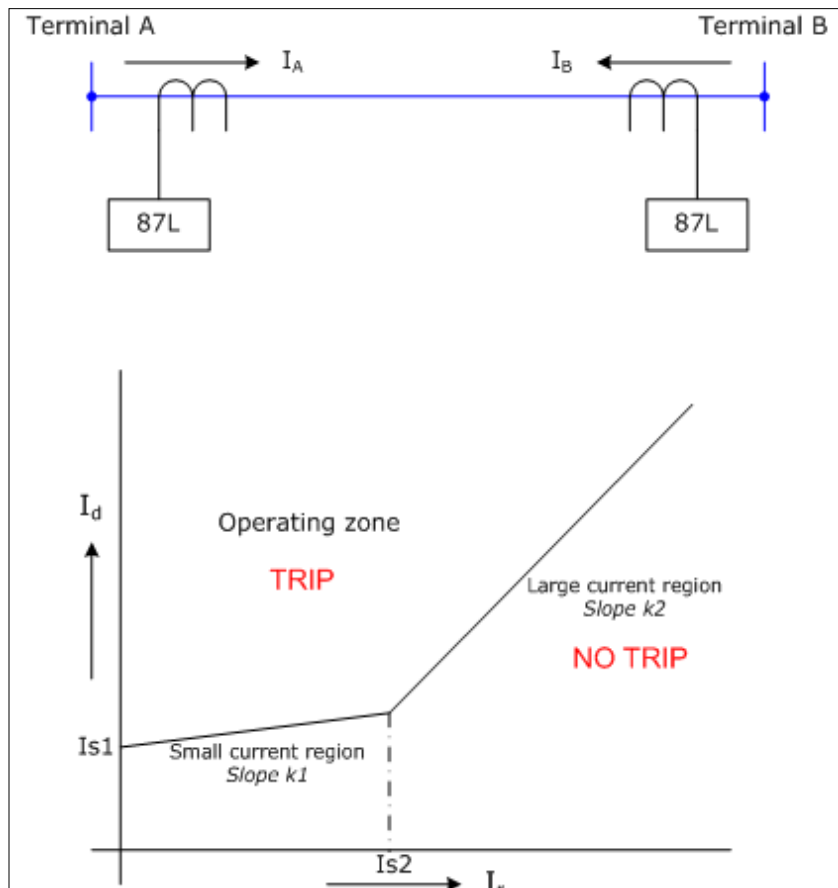

Figure 1 - Dual Slope Restraint Characteristic

Charge comparison relaying is similar to percentage differential but compares the total charge transferred during each half cycle to the corresponding half cycles at the other end(s) of the line. It can reduce the demands on the communication system because only the total charge measured at each end needs to be sent and the timing needed to coordinate half cycles may be less precise than to coordinate sampled currents within the waveform.

The alpha plane measuring principle is based on calculating the complex ratio of the remote currents to the local currents. The ideal restraint location in the alpha plane is -1 regardless of current magnitudes. The effect of errors in current magnitude at one end will be to shift the apparent fault condition in the alpha plane along the real number axis. The effect of errors in the angle, such as the forward shift during CT saturation or due to communication delays, move the apparent fault condition off of the real number axis.

To accommodate these errors the restraint characteristic is composed of two circular arcs enclosing the ideal restraint location, each centered at the origin of the alpha plane, and two boundaries lying on radii also centered on the origin of the alpha plane. To accommodate local and remote symmetry in sensitivity, the radius of the inner circular arc is the reciprocal of the radius of the outer arc. Figure 2 shows the alpha plane line current differential characteristic.
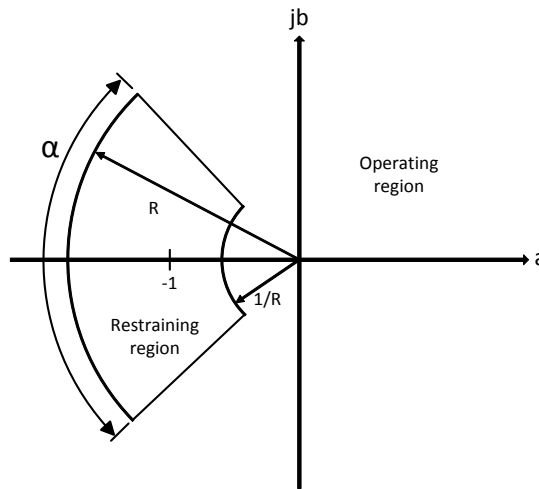

Figure 2 - Alpha plane line current differential characteristic

The guide also briefly addresses other current measurement techniques such as Magneto-Optic Current Transformer (MOCT), Rogowski coils, and IEC 61850 process bus sampled values.

4. Communication Scheme Design

As communications are a critical part of a line current differential relay scheme, this guide provides a detailed description of the operation of various types of communications channels. For the relay scheme to operate correctly, the current information needs to be exchanged between line terminals over a reliable communications channel.

While a dedicated fiber optic medium will resolve many channel concerns, it is not always available or cost effective to install. Many applications rely on multiplexers to transport critical relaying. A concern with this type of medium is that the circuit routing and protection of the communication circuit may not be under the control of the relay engineer. The relay engineer is typically required to specify to the communications engineer the minimum channel operating characteristic that will provide a reliable communication path for the application.

While typically providing over 99.9% availability, the reliability of a digital relay channel is affected by data errors, transients, equipment failures, channel switching, varying and asymmetrical propagation delay, atmospheric conditions affecting microwave links, or poor optical connectors and splices. These conditions result in loss of data to the relay, which may require re-synchronization of both the relay and communications equipment. The application guide discusses techniques for reducing these potential problems by utilizing redundant channels, preferably with diverse routing. A common application of this type is to use dedicated fiber for the primary path, and a multiplexer channel as a backup path.

There are many interface options available for interconnection between the relay to the communications equipment, if a direct relay-to-relay connection (direct fiber) is not used. The guide provides a description of several of the most common interfaces, including RS-449, V.35, X.21, G.703, C37.94, and also includes a discussion on IEC 61850 substation to substation communications as it applies to current differential relaying.

Asymmetrical network switching can result in unequal channel delay in the relay transmit and receive directions. This unequal delay time will not be detected with the typical ping-pong delay measurement techniques, and will result in inaccurate time delay compensation values calculated by the relay. Global Positioning System (GPS) timing synchronization, or symmetrical switching, which forces both the local and remote channel equipment to communicate on the same path, both help alleviate this concern.

The guide also discusses the advantages and the backup protection necessary when using GPS signals as a source for relay synchronization. Synchronous Optical Network (SONET) and Synchronous Digital Hierarchy (SDH) require highly accurate timing to maintain synchronization of the network. These networks derive their timing information from primary and backup GPS receivers, providing 1µs timing accuracy throughout the network. SONET and SDH equipment also can revert to internal timing sources, which will maintain network synchronization to within 1 µs accuracy in the unlikely event of total GPS failure. Using relay timing derived from Time Division Multiplexing (TDM) network communications equipment will provide a secure, reliable, synchronized timing signal for all relays connected to the network.

The guide is an excellent reference source for understanding the communication channel requirements for a current differential relay protection application.

5. Application Considerations

Digital line current differential (87L) protection can be applied to several diverse line configurations. The lines can be long or short, single or multi-terminal and have varying voltage levels. This guide addresses many of these configurations and delivers the advantages and/or disadvantages for each configuration.

The use of digital line current differential protection for multi-terminal lines are the most common due to the majority of power system transmission lines being two or three terminal. As the number of terminals increases to three, four or five the complexity of the communications increases. This guide discusses the two most common solutions for reducing this complexity. One solution is to give only certain key relays the capability to receive the current data from all the terminal relays, perform the differential calculations, and make the decision to trip. The other solution is for each relay to sum its current with its adjacent terminal and then pass along the resultant current.

The use of digital current differential for line protection where the terminals are arranged in a breaker-and-a-half configuration is examined. This guide discusses instances where the remote system is relatively weak or significant CT saturation can occur. One example is for a fault to be fed from a weak source at the remote terminal and a large through fault current in the breaker-and-a-half connection, CT saturation errors would manifest themselves as a spurious differential current while relatively small restraint would be produced from the low remote-end currents. One solution for this problem is for the relay to measure both currents separately as shown in Figure 3. The relay system will treat each current as an in-feed and calculate differential and restraint currents as usual. If summation of currents is used, then other techniques such as supervisory logic or additional restraint based on saturation can be used.
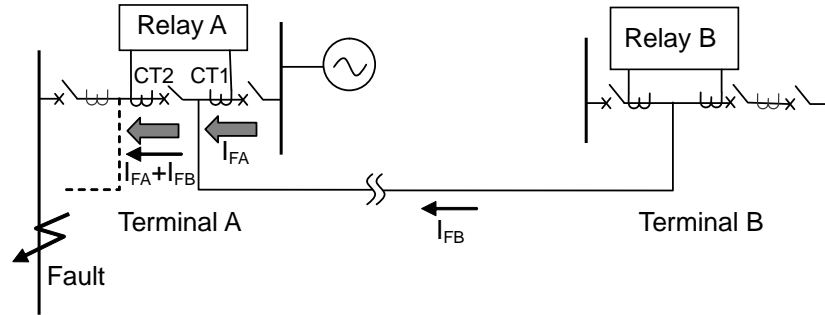
Figure 3 Close-in external fault for breaker-and-a-half bus configuration

Line current differential relays are relatively easy to set when compared to distance relays. However, the balance between sensitivity versus security needs to be considered. There has been a tendency to use the most sensitive setting the relay allows. This is done as an attempt at providing adequate sensitivity with sufficient margin in accounting for the measuring errors that may influence relay sensitivity. However, the increased sensitivity will sacrifice security and false trips for external faults may occur due to the same measuring errors that motivated increased sensitivity. The use of zero and negative sequence differential elements may improve the sensitivity.

This guide discusses several conditions and designs that need special consideration. Open CT conditions occur when local or remote current transformers are opened or shorted anywhere within their circuit including the cabling, test switches or even the relay current inputs. Under normal load, an open CT condition could produce an undesirable operation from a differential protection scheme. It is also possible that damage to the secondary equipment resulting from high voltage produced from an open CT circuit could occur. Solutions are available to detect, alarm, and/or block functions for these conditions. For designs that use different types of CTs at each end, the relay can correct for different ratios but considerations are also addressed for different characteristics and for potential saturation issues. Various methods are discussed in the guide for handling charging current. In addition to these subjects, CT saturation, stub bus, series compensated lines, and shunt reactors are discussed. The guide also mentions the advantage of line current differential relay in that it is not impacted by mutually coupled lines, weak infeed conditions or out-of-step conditions.

The use of single phase tripping and reclosing enhances the stability, power transfer capabilities, reliability and availability of a transmission system during and after a single-line-to-ground fault. Line current differential relays, where individual phase currents are compared from end to end, facilitate the use of single phase tripping and reclosing.

A special case for line current differential in-zone protection exists when a transmission line is terminated with a transformer in series with it, or a transformer is tapped off of the transmission line. This is typically a product of economic considerations where breakers with CTs are not installed on the high voltage and low voltage terminals of the power transformer. This guide discusses the issues associated with these types of arrangements.

This guide also briefly addresses how to handle communication channel failures and how to utilize a communication channel cutout switch to disable the current differential schemes for certain operational scenarios.

6. Testing and Troubleshooting

Typically, the following three methods of relay testing are used for commissioning a current differential relay system.

— Loopback testing

— Local relay back-to-back bench testing

— End-to-end time synchronized relay system testing

Loopback testing is probably the least desirable method of testing. This test requires connecting the relay transmit and receive ports together. Depending upon the type of communications, this may require a simple fiber optic patch cord, or an electrical loopback connector, and in the case of digital communications possibly, an external clock to emulate the communications network timing. The relay transmit and receive addressing will need to be disabled, or made compatible.

With the communications looped, the relay will be receiving remote currents that are always in phase with the local current and thus calculate an internal fault condition. Other than testing minimum pick up points, this test setup prevents testing relay restraint, tapped load conditions, or confirming correct end to end current phasing. If the communications channel is available, it can provide a loopback at the remote terminal, and confirm the relay channel integrity.

Local relay back-to-back bench testing is testing from one location with at least two relays. Consider a two terminal line with new 87L relays on each end. Prior to installation, either obtain both relays or acquire another relay where a bench test could be done with fiber jumpers as the communication medium. Three phase test equipment with laptop, software program for testing, and the establishment of a communication channel would be required.

With the actual relay settings for the line relays, one could perform automated relay testing with each relay communicating with each other. The relay settings engineer could also provide fault simulation test data for "go/no-go" test evaluations. The success of these tests would give sufficient confidence that the line could be energized with the newly set relays once the communication channel has been validated.

End-to-end time synchronized relay system testing involves testing the protection scheme including the communication channels, and excluding the current transformers, when only secondary current injection is performed. It verifies the overall wiring from the injection points. GPS time-synchronized three-phase test sets, laptops, and test personnel are required at each terminal.

Testing verifies that the protection configuration and settings, including any compensation for current ratio, phase shift, and zero-sequence elimination, if required, are correct at all ends. The current differential operating/restraint characteristics are also tested as a complete scheme to verify that all ends are set correctly by performing "go/no-go" simulation tests near the characteristic boundaries for low and high current values, and at the limit angles of the characteristic. Modern test systems with prepared test plans allow automatic calculation of injection test values based on the settings provided by the setting engineer.

Additional end-to-end tests may also be performed based on fault simulation studies for internal and external faults of various types and fault resistances to test for operating times and stability for external faults. The metering facilities of numerical relays and on-line measurement and visualization features of the relay software while injecting currents help in the verification testing.

Troubleshooting is an activity taken in response to a protection relay system that did not perform as expected. When a misoperation occurs, whether the system operated for a fault outside its zone of protection or failed

to operate, data is gathered to determine all the necessary information about the event. Events records, such as oscillography and sequence of event data, are obtained from the relays and digital fault recorders, if available, and are then analyzed to determine which protective relay elements did or did not operate in reference to a time source.

If event records are unavailable, a troubleshooting investigation is still performed in an effort to find the cause of the misoperation problem. Tasks in this effort include: communication channel integrity checks, all wiring check for tightness and accuracy, and re-analysis of the relay settings for correctness.

An example of a real misoperation that occurred on a line current differential protection system was deemed to be caused by a relay setting error. The relay setting was applied, programmed into the relays as provided by the relay settings engineer and was not realized to be in error until the line fault and misoperation. During commissioning, an accurate end-to-end test may not have been performed; otherwise the setting error may have been found early.

Newer relay systems of today have alarming indication that is monitored via SCADA that alerts dispatch operators of a communication channel issue.

Assuming that all due diligence has been applied when a current differential scheme is initially commissioned, invariably over the life of the scheme; some troubleshooting may need to be done associated with the communication channel. There are a wide range of causes for a current differential scheme to become intermittent, to fail in a "safe" mode, or to occasionally fail with evidence of a "misoperation".

7. Conclusion

The C37.243 IEEE Guide for Application of Digital Line Current Differential Relays Using Digital Communication is a practical reference for the engineer who is working with line current differential schemes. The guide closes with an appendix on the subject of non-traditional instrument transformers. The guide also includes a comprehensive bibliography with additional information on numerous topics related to line current differential protection.