What's New in C37.113^{TM}-2015, IEEE Guide for Protective Relay Applications to Transmission Lines

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Abstract— **This paper provides a summary of the changes that were made to IEEE Standard C37.113^{TM}-1999, IEEE Guide for Protective Relay Applications to Transmission Lines, in its revised version of 2015. Topics include the selection of communication systems, redundancy, autoreclosing, ground overcurrent protection, line length and source impedance ratio considerations, lines terminated into transformers, current differential applications, ground path configurations, effects of high grounding resistance, transfer and stub bus configurations, relay elements used in step-distance schemes, polarization methods, specially shaped characteristics, the role of directional ground overcurrent protection used in conjunction with ground distance relays, single-phase tripping and reclosing, and an annex that discusses both fault and system studies.**

Index Terms — **relay application, transmission line protection**

INTRODUCTION

IEEE Standard C37.113^{TM}-2015 provides application information on the concepts of protection of AC transmission lines. The 1999 version was revised and updated. This paper summarizes the main changes and enhancements. This paper does not merely repeat what is contained in the guide. Instead, the guide will need to be referred to for detailed information on the topics that this summary paper discusses.

SECTIONS

A. Communications

The guide discusses reasons for using communication systems in transmission line protection. Communication systems allow for high-speed clearing of faults. Some reasons that this is advantageous include improved stability, reducing equipment damage, high-speed autoreclosing, limiting duration of voltage sag, and providing better fault clearing for multi-terminal lines or weak infeed terminals.

For lines which will utilize a communication-based protection scheme, various considerations related to the communication system are discussed. Some of these considerations include the number of systems required, the type and medium of communication system, the need for alternative paths, and operational and maintenance issues.

B. Redundancy and Backup Considerations

The Redundancy and Backup Considerations section has been completely re-written from the 1999 (reaffirmed 2004) version (which was section 3.3). The revised version expands upon the previous language and now includes several examples.

The guide now explicitly defines both redundant and backup protection:

> **Redundancy is the design of relaying developed with the goal of avoiding the possibility that a single component failure will prevent the relaying from reliably sensing and isolating a fault in the protected zone. Backup protection is a form of protection that operates independently of specified components in the primary protective system. It may duplicate the primary protection or may be intended to operate only if the primary protection fails or is temporarily out of service.**

Many transmission lines are protected by two protection systems. Protection systems are deemed to be redundant when both protection systems operate independently and do not share any components.

Backup protection is achieved by using different protection systems or functions. These systems function simultaneously with the primary protection systems but their operation may or may not be time-delayed. Time delayed backup systems perform the tripping function only if the primary protection systems fail to isolate the faulted line.

The guide provides a helpful commentary on the considerations and tradeoffs involved in the design of redundant and/or backup protection.

C. Autoreclosing Methods

Although this section acknowledges that automatic reclosing is discussed in detail in IEEE Std C37.104™, comments are provided for ready reference for the readers. This section discusses criteria entities may use for selecting automatic reclosing schemes. The two most commonly applied methods of automatic reclosing, high-speed and time-delayed, on transmission lines are described and discussed in some detail as are the benefits of using either scheme.

More information about single-phase reclosing is given in Section O of this document.

D. Sensitive Ground Overcurrent Fault Protection

Sensitive ground overcurrent fault protection is used to reduce hazards to public and to protect equipment. While faults with fault impedance are not as common on the transmission system as in distribution systems, the severity and adverse consequences of a transmission-line fault that is not detected can be significantly higher due to the high energy levels that are present.

The type of system grounding and specific fault impedance determine the magnitude of ground fault current. Faults that contain high impedance pose a challenge to distance relays. Ground overcurrent relays may be set sensitive enough to detect these faults, but they could adversely impact security.

Due to an increased focus on sensitivity, factors that were previously accounted for in general tolerances have now become more important, and consideration for such factors is required. These factors include maximum ground current (due to system imbalance) during heavy loads, the system model, mutual coupling, instrument transformer inaccuracies, single phase tripping, and contingencies.

The selection of the time delay curve is a matter of preference. However, the sensitive ground overcurrent relay should coordinate with ground distance relays and other ground overcurrent relays. In order to improve the coordination of the ground distance protection functions, trip times for line-end ground faults should be longer than zone 2 delays with a margin. Coordination with other similar relays at remote terminals should be achieved for fault current levels defined by the expected fault impedance in an application.

Directional ground overcurrent protection may be applied to provide backup protection to impedance relays. The coordination of all elements that are used in a protection scheme must be carefully checked against each other. This checking is easier when only one type of element is used. However, most protection schemes use a combination of definite-time and time-overcurrent functions that include both impedance and overcurrent elements. The guide discusses items to be considered when coordinating these various elements.

E. Line Length and Source Impedance Ratio Considerations

The length of a transmission line can influence the selection of the scheme for protecting the line. Transmission lines may be classified as short, medium, or long. A line is designated short if the source impedance ratio (SIR) for the line is large. Transmission lines that have SIR greater than four (4) are classified as short lines. The lines that have SIR of 0.5 to four (4) are classified as medium lines. Finally, lines that have SIR of less than 0.5 are classified as long lines. Although the physical length of lines is a factor in the SIR, it is inappropriate to describe the line as long, medium, or short based merely on the physical length of the line.

A suggested method to calculate the source impedance for the purpose of classifying line length is to place a short circuit at the remote bus (boundary of the line zone) and calculate the source impedance as the voltage drop from the source to the relay location divided by the fault current.

It is often desirable to determine the SIR under N-1 conditions as well to determine if the line becomes short when the strongest source behind the local terminal is out of service.

The process for determining the SIR for ground faults is very similar to that used for phase faults and is described in more detail in the guide.

F. Considerations for Line Distance Applications

The “Lines Terminated into Transformers” section has been expanded in the guide to discuss the protection issues presented by the location of CTs and VTs when there is an inline power transformer. For these cases, economic or other factors may dictate the use of VTs and/or CTs measuring the low side quantities V_L and I_L (Bus A side) of the transformer. These factors introduce additional application considerations, which are primarily the effects of the transformer impedance, phase shift introduced by wye-delta transformation, tap changers, secondary impedance calculations, and the availability of ground fault (zero sequence) current. Therefore, careful consideration should be given to the placement of VTs and CTs for these line distance applications. Figure 1 shows a typical application.

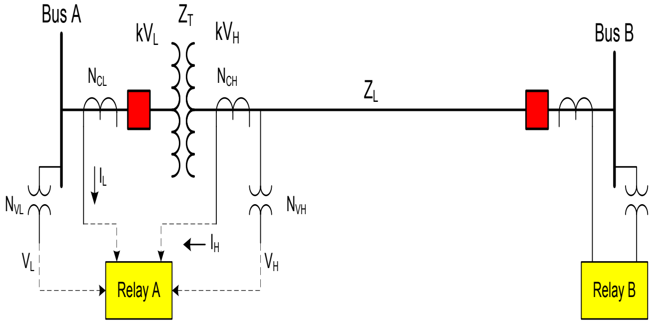

Figure 1—Typical transformer-line combination

The guide describes four connection alternatives for lines terminated into transformers and protected with instantaneous, under-reaching step distance relays (generally zone 1).

Alternative 1: Using VTs and CTs from the line side of the transformer, V_H and I_H, as shown in Figure 1, is the preferred solution. This arrangement separates the line and transformer into two separate zones of protection supervised by separate relays.

Alternative 2: Using voltage from the high-voltage side of the transformer, V_H, and current from the low-voltage side of the transformer, I_L. Wye-delta connected transformers introduce a 30° phase shift between I_L and I_H that needs to be taken into consideration. The impedance reach is measured from the high or line side voltage transformer providing V_H while the currents are measured from the low or bus side with the power transformer in between.

Alternative 3: Using both voltage and current from the low-voltage side of the transformer (V_L and I_L). This is generally a more practical connection when both VTs and CTs on the line side are not available. The zone 1 reach should be set at less than Z_T plus line impedance Z_L, so as not to overreach the remote bus. This connection method has a disadvantage of limiting the reach of line protection when Z_T is large compared to Z_L.

Alternative 4: Using voltage from the low-voltage side of the transformer, V_L, and current from the high-voltage side of the transformer, I_H. Using these connections, the impedance reach is measured from the bus that provides V_L and its setting should include the transformer impedance Z_T plus line impedance Z_L.

The disadvantage of having the transformer impedance in the zone 1 setting applies to Alternative 4 in the same manner as it does to Alternative 3. In addition, since fault direction is determined from the CT location, faults in the transformer cannot be detected.

G. Considerations for Current Differential Applications

The guide introduces considerations for current differential protection for lines terminated into transformers. The issue of whether the transformer high side or low side current transformer is used for the line relaying is examined. In addition, the effects of the transformer connection type, tap changers, and inrush are discussed.

H. Ground Path Configurations

Section 4.6, “Ground source configurations”, in the 1999 version was replaced by section 5.7, “Ground path configurations”, in the 2015 version. It covers grounding in more detail and gives an overview of how ground current flows from the fault location back to possible sources such as delta - grounded Y transformers.

Figures 2 and 3 show an example of a small system and its associated sequence network illustrating the ground current path, where

Z_{G1} = Generator positive sequence impedance,
Z_{G2} = Generator negative sequence impedance,
Z_{G0} = Generator zero sequence impedance,
Z_T = Step Up Transformer impedance,
Z_{PS} = Auto-transformer primary-secondary impedance,
Z_{P0} = Auto-transformer primary zero sequence impedance,
Z_{S0} = Auto-transformer secondary zero sequence impedance,
Z_{T0} = Auto-transformer tertiary zero sequence impedance.

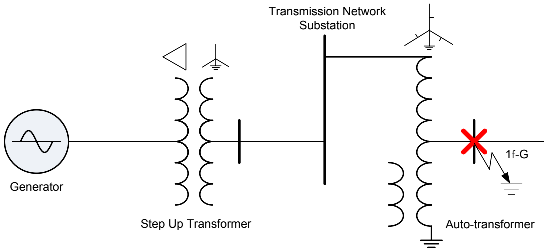

Figure 2—Single line for phase-to-ground fault

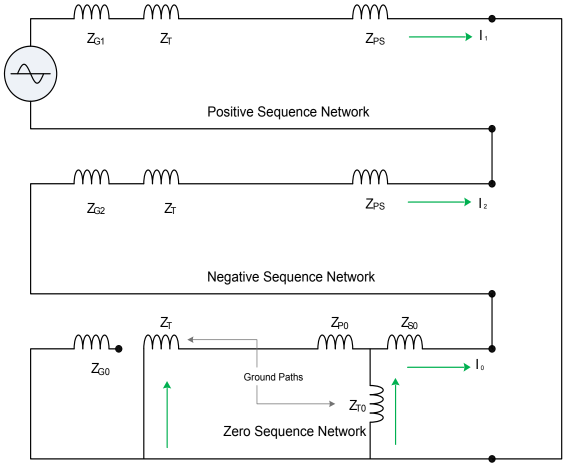

Figure 3—Symmetrical Component Diagram

Effectively grounded and impedance grounded systems are explained and compared. Adding impedance to the ground path reduces ground fault currents to appropriate levels.

For a system to be effectively grounded according to IEEE Standard 142, it should have a sufficiently low impedance such that for all system conditions the ratio of zero-sequence reactance to positive-sequence reactance (X0/X1) is positive and less than 3, and the ratio of zero-sequence resistance to positive-sequence reactance (R0/X1) is positive and less than 1.

Impedance grounded systems can use either reactance or resistance; however, reactance is predominately used.

There are three different types of reactance grounded systems: high, low and resonant. High reactance grounded systems are not used in transmission. Resonant systems using Petersen Coils are mostly used in Europe where the coil is sized to match the system's capacitance to ground. This neutralizes the fault, allowing the arc to be quickly extinguished without opening a breaker. Low reactance grounding, normally through transformers, is sized to achieve a desirable X0/X1 ratio.

I. Effects of High Grounding Resistance on the Operation of Line Protection Systems

The guide outlines the challenges that high-resistance ground faults present to the protection of transmission lines and provides considerations to mitigate this issue. An example showing the response of ground fault protection systems during high-resistance ground faults is provided in the guide. The example describes how relays respond to fault impedance at different locations on the line. The guide illustrates that the fault resistance coverage is worst at the middle of the line because that is the worst case for either terminal to detect the fault simultaneously. After one end clears the other end will see an increase in fault current and have a better chance at detection.

J. Transfer Bus and Stub Bus Configurations

Clause 5.12 of the guide considers the effect of the bus configuration on line protection. Six basic configurations for terminating transmission lines (single breaker, breaker-and-a-half, double breaker, double bus, ring bus, and transfer bus) are described in detail by IEEE Std C37.234™. These do not typically affect line protection except where selection of the voltage source for the line protection is concerned, whether it is located on the bus side or on the line side of the circuit breaker. An exception is the transfer bus configuration that includes one extra breaker, the "bus coupler breaker", to serve as a substitute while any other circuit breaker is removed from service. This is done without circuit interruption using disconnectors and switches to reconfigure the bus layout and physical relay connections. One method uses multiple setting groups from relay(s) dedicated to the bus coupler breaker to protect the circuit of the "bypassed" breaker.

Stub bus protection is needed when a local disconnect switch in series with the protected line is opened to separate the line for maintenance or repairs while the line breakers of a breaker-and-one-half or ring bus remain closed to maintain bus continuity. Erroneous or no voltage measured from the line side VTs can cause failure or misoperation of distance, directional, or differential line relays if unmitigated. Stub bus considerations are also addressed by IEEE Std C37.234™ and in IEEE Std C37.243™.

K. Relay Elements in Step Distance Schemes

For each protective zone, three relay elements are needed for detecting multi-phase faults. They are for: 1) A-B faults, 2) B-C faults, and 3) C-A faults. Similarly, for each zone of protection, three relay elements are needed for detecting single-phase-to-ground faults. They are for: 1) A-G, 2) B-G, and 3) C-G faults. Tables 5 and 6 of the guide show the combinations of phase voltage, phase currents, and zero sequence current used to detect each type of fault.

L. Polarization Methods

The most common methods of directional ground current relay polarization are zero-sequence voltage, zero-sequence current, and negative-sequence polarization. However, other polarization methods do exist. Other methods, including dual, negative-sequence impedance, zero-sequence impedance, and virtual polarization, are discussed in the guide.

Undesired tripping can occur on transmission lines protected by a directional comparison pilot scheme for remote ground faults where different polarizing methods are used at the two terminals of the line. An example of a case where a misoperation can occur because of mismatched polarizing methods on a line is discussed in the guide.

M. Specially Shaped Characteristics

The document discusses how modifying distance relay characteristics can make them more sensitive to faults while remaining secure for heavy loads. Methods available include reshaping the characteristic itself, such as using a quadrilateral or lenticular, or supervising the circular mho element with "straight-line" load blinders or "cone-type" load encroachment elements. Regarding the latter method, it is noted that during faults the load blinder/encroachment supervision can be bypassed to allow the full mho characteristic to operate, and methods for accomplishing this are provided, including current unbalance and phase undervoltage. Each method should be carefully evaluated for both fault coverage and intended load carrying capability.

N. Single-phase Tripping and Reclosing

In a single-phase tripping scheme, only the faulted phase of the transmission line is opened for a single line-to-ground fault, while all phases are tripped for any multi-phase fault. Two ends of the transmission line remain connected by two phases when a single phase to ground fault occurs and single-phase tripping takes place to isolate the fault. The single pole that was tripped would typically reclose after a time delay. Stability studies typically show that there is improvement in system stability and power transfer capability when single-phase tripping is applied.

Application of single-phase tripping requires attention to a number of details that are not considered for three-phase tripping schemes, or that need special consideration for single-phase tripping. These include

- Faulted phase selection
- Arc deionization
- Automatic reclose considerations
- Pole disagreement
- Effects of unbalanced currents

Single-phase tripping and reclosing applications impose extra requirements on both circuit breakers and relays. Each pole of the circuit breaker must be operated independently.

The primary line protection must be phase-selective, meaning that the protection system can correctly identify single-phase to ground faults and trip only the faulted phase. Phase segregated line current differential and phase comparison schemes are inherently phase selective and do not generally require additional phase selection logic.

While the pole is open during the single-phase autoreclose cycle, protection coverage must be maintained for the two phases that remain energized. Special logic must be designed into the protective relay so that the protection elements remain secure during the open pole condition and are also able to properly detect faults during the open pole time.

Several auxiliary protection and control functions need to be augmented to support single-phase tripping and reclosing, such as breaker failure, open phase detection, and loss of potential. The breaker-failure and open-phase-detection functions need to identify failed breaker operations or open phase conditions on a per phase basis. Loss-of-potential detectors may require blocking from the open-phase function to avoid spurious operation during single-phase autoreclose dead time.

Single-phase autoreclosing typically employs elaborate sequences depending on the fault type and shot count. The reclose open interval in single-phase tripping applications is typically longer than the reclose open interval used in three-phase tripping applications. The longer open interval is needed to allow the arc more time to extinguish in single-phase tripping applications.

In general, a variety of operating modes and philosophies could be used for reclosing after single-phase tripping. The schemes are complex and should be carefully studied before they are applied.

Breaker failure functions need to be specially designed to support single-phase tripping operations. IEEE Std. C37.119™ provides detailed discussion on this topic.

O. Annex A: System Studies Needed for Setting Relays

The guide includes an annex covering fault studies and special studies such as transient stability and load flow studies. The results of these studies are important inputs towards selection, application, and operation of protection schemes and development of relay settings.

CONCLUSION

The C37.113^{TM}-2015 IEEE Guide for Protective Relay Applications to Transmission Lines is intended to assist protection engineers in applying relays and protection systems to protect transmission lines. The guide includes a wealth of information on transmission line protection as well as an extensive bibliography.

REFERENCES

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