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IEEE Guide for Power-Line Carrier Applications

IEEE Power Engineering Society

Sponsored by the
Power System Communications Committee



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IEEE Guide for Power-Line Carrier Applications

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Power System Communications Committee
of the
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Abstract: The purpose of this guide is to provide application information to users of carrier equipment as applied on power transmission lines. Since the major applications of the power-line carrier (PLC) is for protective relaying, special consideration for these applications has been included. Information related to the expanding usage of carriers on distribution lines below 69 kV is not specifically covered. Detailed equipment design information is avoided as this is primarily the concern of equipment manufacturers.

Keywords: carrier equipment, intrabundle conductor systems, insulated shield-wire systems, power-line carrier, power transmission lines

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Introduction

This introduction is not part of IEEE Std 643-2004, IEEE Guide for Power-Line Carrier Applications.

Since the first release of this document in 1980, many additions have been made to the information presented. The first release was to replace a 1954 AIEE Committee Report, Guide to Application and Treatment of Channels for Power-Line Carrier. This revision hopes to clarify areas where technology has improved as well as to add sections specifically concentrated to protective relaying applications. Although there are still uses in North America of the power-line carrier (PLC) for voice and supervisory applications, the predominate application is for dedicated protective relaying channels. To accomplish this task, the Power-Line Carrier Subcommittee of the Power Systems Communications Committee worked closely with the Communications Subcommittee of the Power Systems Relaying Committee through parallel working groups in both committees.

Details of the changes would be too numerous to note here. This guide is both a reference for the experienced PLC engineer as well as for the novice.

PLC is not unique to only North America. Although it is not possible to describe differences in applications and philosophies, the principles presented here remain the same worldwide.

This guide is dedicated to Mr. Herb Dobson, posthumously, as he was a noted expert in the field of PLC and contributed significantly to its widespread usage and the information in this guide.

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IEEE Guide for Power-Line Carrier Applications

1. Scope

The purpose of this guide is to provide application information to users of carrier equipment as applied on power transmission lines. Since the major applications of the power-line carrier (PLC) is for protective relaying, special consideration for these applications has been included. Information related to the expanding usage of carriers on distribution lines below 69 kV is not specifically covered. Detailed equipment design information is avoided as this is primarily the concern of equipment manufacturers.

Material on PLC channel characteristics is presented along with discussions on intrabundle conductor systems and insulated shield-wire systems. Procedures are provided for the calculation of channel performance. Data for the calculations are drawn from various sections of the guide. The coupling components considered are line traps, coupling capacitors, line tuners, coaxial cables, hybrids, and filters. Frequency selection practices and future trends are discussed.

An effort has been made to coordinate this guide with the CIGRE Guide [B49]¹ and IEC 60353,² IEC 60481, IEC 60495, and IEC 60663.

2. Normative references

The following referenced documents are indispensable for the application of this guide. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ANSI C63.2, American National Standard for Electromagnetic Noise and Field Strength Instrumentation, 10 Hz to 40 GHz—Specifications.³

ANSI C93.1, American National Standard Requirements for Power-Line Carrier Coupling Capacitors and Coupling Capacitor Voltage Transformers (CCVT).

ANSI C93.3, American National Standard Requirements for Power-Line Carrier Line Traps.

¹The numbers in brackets correspond to those of the bibliography in Annex B.

²Information on references can be found in Clause 2.

³ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

ANSI C93.4, American National Standard Requirements for Power-Line Carrier Line—Tuning Equipment.

ANSI C93.5, American National Standard Requirements for Single Function Power-Line Carrier Transmitter/Receiver Equipment.

IEC 60353, Line Traps for A.C. Power Systems.⁴

IEC 60481, Coupling Devices for Power Line Carrier Systems.

IEC 60495, Recommended Values for Characteristic Input and Output Quantities of Single Sideband Power-Line-Carrier Terminals.

IEC 60663, Planning of (Single Sideband) Power Line Carrier Systems.

IEEE Std C37.90.1TM, IEEE Standard for Surge Withstand Capability (SWC) Tests for Protective Relays and Relay Systems.

IEEE Std C37.90.2TM, IEEE Standard for Withstand Capability of Relay Systems to Radiated Electromagnetic Interference From Transmitters.

IEEE Std C37.90.3TM, IEEE Standard Electrostatic Discharge Tests for Protective Relays.⁵

3. PLC channels

A PLC channel includes the signal path from the transmitting electronic equipment at one terminal, through its coupling equipment, over the power line, through the tuning equipment at the receiving end, and into the electronic equipment at the receiving terminal. In bidirectional applications, a similar return path is provided.

As shown in Figure 1, a basic PLC system consists of three distinct parts: the terminal assemblies, the coupling equipment, and the transmission line. Terminal assemblies consist of transmitters, receivers, and protective relays. The coupling equipment consists of the line tuner, coupling capacitor, and line trap. The coupling equipment provides a means of connecting the terminals to selected points on the power transmission line. The transmission line provides a suitable path for the transmission of carrier energy between terminals in the PLC band of frequencies. At the terminals, one or more transmitters and/or receivers may be required, depending on the number of functions to be performed.

⁴IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembe, CH-1211, Genève 20, Switzerland/Suisse (<http://www.iec.ch/>). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

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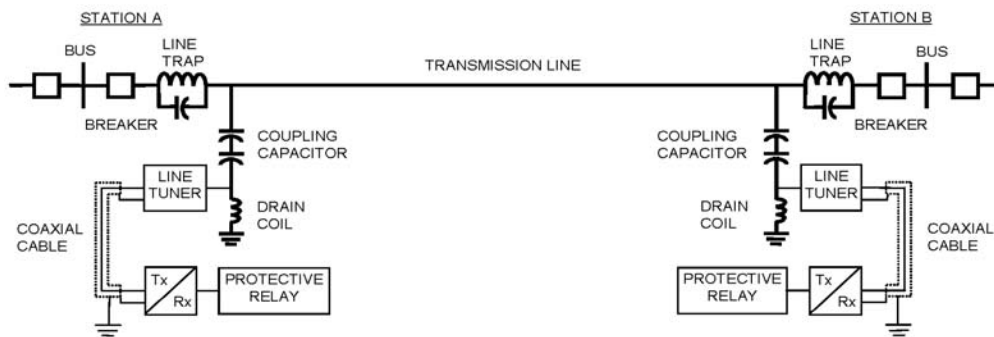


Figure 1—Diagram of a PLC channel

Coupling of carrier energy to the transmission line is accomplished by the coupling capacitor, which is the physical link to the transmission line that has a high impedance to the power frequency and a low impedance to carrier frequencies. The drain coil, which is part of the coupling capacitor (or additionally in the line tuner), provides a low impedance path to ground for power frequencies and a high impedance path for carrier frequencies. The user should also be aware that if an optional drain coil is placed in the line tuner, the parallel combination of the two drain coils should be considered (refer to 7.3.4). The line tuner provides impedance matching between terminal assemblies and the transmission line. It also provides for resonant tuning with the coupling capacitor. The line trap is inserted into power lines to minimize the loss of carrier energy and to prevent external faults from shorting the carrier signal on the unfaulted line. The transmission line provides the path for the PLC energy.

PLC is a technique by which low radio-frequency (RF) currents are propagated over metallic conductors, which may be either ac or dc overhead transmission lines or pipe type cable. The primary difference between high-voltage (HV) power transmission and PLC transmission is the frequency of operation. Although the fundamental principles of both transmissions are the same, many factors of primary importance at PLC frequencies are negligible at power frequencies.

Frequencies in the range of 30–500 kHz have been employed for PLC. This frequency range is high enough to be isolated from the power frequency energy and the noise it creates, but not so high as to encounter excessive attenuation. Although frequencies somewhat lower than 30 kHz can be used, it is difficult to efficiently couple these frequencies to the transmission line by using coupling capacitors.

Anytime voltage is discussed or V is used in an equation in this guide, it is always RMS voltage unless otherwise specified.

4. PLC applications

4.1 Relaying applications

4.1.1 Interfacing PLC with relays

Many factors determine the form taken by the power-line carrier–relay interface, among which are the type of protection scheme, the channel speed requirements, and the distance from the PLC equipment to the relays. This distance, if excessive, can affect both the output and the keying input conditions.

The current generation of PLCs all use optically isolated low-energy keying inputs and solid-state outputs. Some users have found that, when the carrier set is separated from the protective relays, the keying leads can pick up enough noise to key the carrier. One possible solution is to install an electromechanical relay at the carrier set to key the carrier. This relay will usually not be affected by the noise picked up by the keying leads, but it will delay the keying by the relay's pickup time.

4.1.2 Carrier operation types

Two basic types of PLC channels are used most commonly in protective relaying schemes in North America: single-function ON–OFF [amplitude modulated (AM)] and single-function frequency shift keyed (FSK). Single-function ON–OFF carriers are primarily used in blocking schemes. Single-function FSK carriers are used in permissive, unblocking, and direct trip protection schemes.

4.1.2.1 ON–OFF carrier

The ON–OFF carrier scheme uses an AM signal transmitted via the power line to communicate relay logic to the remote relay terminal. The signal is either on or off. In directional comparison blocking (DCB) schemes, the local relay sends carrier (block) when the fault is external (reverse) to the protected line. The block is sent continuously as long as the local relay senses a fault in the external (reverse) direction. The blocking signal received at the remote relay blocks the remote relay fast trip elements. In phase comparison schemes, the local relay initiates a carrier signal in phase with a (sequence filtered) model of the local end fault current. The phase of the carrier signal received at the remote end is compared with the phase of a (sequence filtered) model of the remote end current to determine if the fault is on the protected line or outside the protected line.

4.1.2.2 FSK carrier

The FSK carrier employs a two- or three-state frequency-shifted signal that is used to transmit relay information to the remote end of the protected zone. The normal signal is called a guard signal and is monitored at the receiving end for continuity. To signal the remote end, the frequency is shifted up or down a specified amount. The simplest FSK scheme is a direct transfer trip (DTT) scheme. A guard signal is continuously transmitted. When keyed, the transmitter shifts from guard to the trip frequency. The receiver will then operate to trip a breaker.

Other schemes employing FSK are permissive transfer trip, directional comparison unblocking (DCU), and phase comparison unblocking. In the latter two schemes, the normal and shifted frequencies are often given special names to denote their function. In DCU, the normal frequency is usually called “block” rather than “guard” and the shifted frequency is “unblock.” In phase comparison unblocking, the two frequencies are called “mark” and “space.”

4.1.3 Protection system design using PLC channels

The power-line carrier provides a manner of communicating protection information between the terminals of a transmission line. The engineer must take into account the special characteristics of PLC in the design of the protection logic.

If the transmission line to which PLC equipment is applied is faulted, the PLC signal being sent may be attenuated by the fault. If the attenuation is so great as to cause the signal to fall below the remote PLC receiver threshold, the remote receiver will squelch and its output will indicate that no signal is present. Each type of protective relaying scheme that uses PLC equipment compensates for the channel characteristics differently. The protection system must be designed with additional logic and timers to cope with PLC signal attenuation conditions.

4.1.4 Directional comparison

Directional comparison includes schemes that use directional relays for fault sensing and PLC for the communications channel. There are several types of directional comparison schemes.

4.1.4.1 DCB

In this protection scheme, the carrier tripping relays are directional and are set to overreach the remote end of the protected line. The carrier tripping relays will initiate tripping for a detected fault unless a carrier block signal is received.

For a fault beyond the remote terminal, the reverse looking blocking relays at the remote terminal will see the fault and key their carrier to send a block signal to the local terminal. Since the local tripping relays are picked up, the failure of the block signal to be received will result in tripping of the local terminal. Internal faults will be sensed by the tripping relays on both ends and no blocking signals will be sent; therefore, high-speed tripping will occur at both ends.

Most schemes use an offset mho multiphase relay and a nondirectional ground relay to start the blocking signal transmitter. If the tripping relay picks up, it will stop the blocking signal, which allows the remote end to trip if its tripping relays are picked up.

The DCB scheme uses the ON-OFF carrier almost exclusively for its communications. Each transmitter sends the same frequency, or the frequencies will be slightly offset. Three terminal applications of DCB will have the frequencies slightly offset to avoid signal cancellation, which might otherwise lead to tripping of some terminals.

Each DCB transmitter is normally off. For external faults only, one terminal will see the fault as external and send a blocking signal to the remote end(s) of the line. Receipt of a remotely sent block signal prevents the local overreaching tripping elements from tripping the local breaker as long as the block signal is received within the coordination timer setting and the blocking signal remains until the fault is cleared.

A coordinating timer is required to allow time to receive the block signal from the remote end transmitter. These timers delay tripping from 3 ms to 12 ms. They are typically set at 8 ms, which means that once a fault is sensed by the tripping relays, there will be an 8 ms delay to wait for the blocking signal. If no signal is received, the trip path will be completed, which thereby trips the breaker. Transient blocking timers are also required to prevent remote tripping on current reversals with parallel lines.

Since the normal state is for the carrier to be off, some sort of testing must be provided to prove the integrity of the channel and carrier equipment. This periodic testing will help prevent most misoperations for failure of the carrier equipment. This testing is typically done with some sort of manual or automatic checkback equipment. See Clause 10.

The keying of the blocking signal should be accomplished by using the contact opening carrier start. In this manner, there will be no interruptions (holes) in the blocking carrier from contact bounce. This usually uses a “b” contact, which opens to remove either positive or negative voltage from the carrier keying circuit. If a solid-state output is used from the relay, then contact bounce is not a problem. Many new digital relays are supplied with contact opening carrier start outputs. It is very important for the utility protection engineer to remember why open contact keying is needed. A contact closing carrier start will increase the probability of a false trip, which is caused by contact bounce causing holes in the blocking signal. A contact de-bounce circuit may be employed in the input of the carrier set keying circuit to avoid the carrier holes. It must be remembered that the contact de-bounce circuit will cause a delay in the dropout of the blocking signal by the dropout time of the de-bounce logic.

4.1.4.2 DCU

The DCU system uses a single-function FSK PLC channel for transmitting relaying information to the remote end of the protective zone. The scheme consists of directional phase and ground relays looking forward and overreaching the protected line's remote terminals, with a FSK transmitter and receiver at each end of the line. There is a discrete frequency for each transmitter. Each transmitter continuously sends a block signal except when a fault is detected by the overreaching relays.

For a detected internal fault, the transmitter is shifted to an unblock frequency. Receiver logic allows tripping for receipt of an unblock signal or during 150 ms after loss of signal. Loss of signal may occur because of a fault on the line. During that time, if the directional relay picks up, a trip signal will be issued to the breaker. If the relays do not operate within the 150 ms window, the scheme will be locked out. This process prevents erroneous tripping during extended loss of carrier signal.

For an external fault that occurs beyond the remote terminal, the tripping relays pick up at the local terminal and send an unblock signal to the remote end. Because the other end is receiving an unblock signal and the fault is behind it, its tripping relays are not picked up, so no trip command is issued. The local terminal will have the tripping relays picked up, but it is still receiving a block signal from the remote end, so no local tripping will occur.

The advantage of this scheme is that it uses fewer elements and does not require carrier checkback equipment because the carrier signal is continuously transmitted and monitored. The disadvantage is that tripping is delayed by the channel and logic time, plus extra frequencies are needed, i.e., a separate frequency between each transmitter/receiver pair. For three terminal lines, six frequencies are needed.

4.1.4.3 Permissive overreaching transfer trip (POTT)

Overreaching transfer trip schemes use a single-function frequency shift channel and require a channel signal to trip. When using a power line as the channel medium, faults may attenuate the signal, which prevent it from reaching the remote end. Therefore, these systems are not generally used with PLC channels.

4.1.5 Phase comparison

Phase comparison relaying compares the phase angle of the fault currents at the two terminals of the protected line. If the two secondary currents are essentially in-phase, the relays detect an internal fault and initiate a trip to the appropriate circuit breakers. If the two secondary currents are approximately 180 degrees out-of-phase, the relays sense an external fault and do not initiate a trip. To do the comparison, a dependable communication channel must exist between the two ends.

Phase comparison systems are typically current-only, which means that voltage transformer inputs are unnecessary. Except for the segregated phase comparison system, a composite sequence filter current network provides single-phase voltage output proportional to a defined ratio of positive, negative, and zero sequence current input. During a fault condition, the relay converts the single-phase voltage output to a square wave (local square wave) to key the channel to the remote terminal and for comparison with the received signal (remote square wave). Relay logic delays the local square wave by the amount equal to the channel time to provide a more accurate comparison.

Phase comparison systems as used with the carrier are divided into the following three major categories; differences are related to channel equipment and sequence filter outputs:

- a) Single-phase comparison blocking
- b) Dual-phase comparison unblocking
- c) Segregated phase comparison unblocking

4.1.5.1 Single-phase comparison blocking

This type of relay scheme uses the single-function ON–OFF carrier for communications. Outputs of the composite sequence current networks are fed into a squaring amplifier, which keys the carrier to produce a square wave. The relay at the remote end compares the received signal to its local square wave and produces a trip output if an internal fault is detected. Refer to Figure 2.

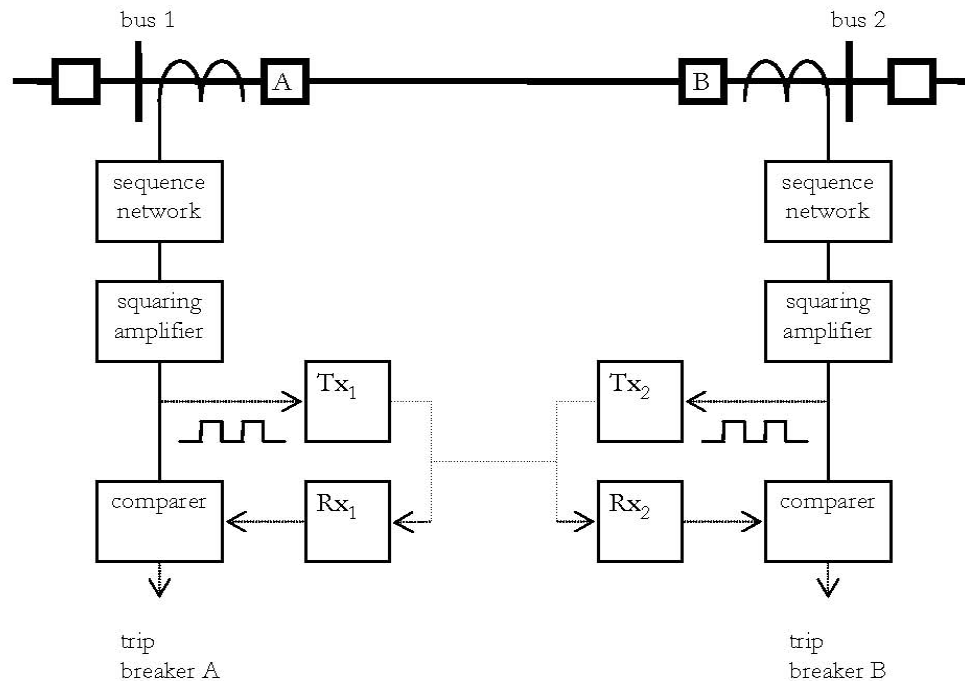


Figure 2—Phase comparison blocking scheme functional diagram

This process is a blocking system because the receipt of a signal is not required for an internal fault. When no signal is received and the fault level detectors are picked up, a trip will occur because the remote signal is not available to negate the internal square wave from the sequence networks. If the fault is external and a carrier failure occurs, either locally or remotely, an erroneous trip will occur because blocking will not be set up.

Two levels of fault detectors are involved with this scheme. The lower level starts keying the carrier with square waves, and the higher level permits tripping on proper comparison.

On lines with high load currents and composite sequence current filter networks including positive sequence, it is not always possible to set the level detectors so they only pick up for faults. Therefore, the relays may be exchanging square waves during non-fault conditions. Impedance relays may be required to supervise fault and level detectors, which would require the addition of voltage transformers to the line.

As an alternative, a phase comparison relay with only negative sequence sensing will be insensitive to the three-phase load. It will also be insensitive to three-phase faults. Therefore, impedance relays will be needed to detect and trip for three-phase faults.

4.1.5.2 Dual-phase comparison unblocking

This type of relay scheme uses the single-function FSK carrier for communications. An FSK transmitter and receiver with separate frequencies are used at each line terminal. Continuous channel monitoring is provided, because either a mark or a space carrier signal is always transmitted.

The output of the sequence networks are fed through the square-wave amplifier into the keying input of the transmitter. The transmitter shifts to mark on the positive output and stays at space for the negative output.

The local signal is fed into two comparators, where one compares the local and remote mark signals and the other compares the space signals. The logic is designed so internal faults produce a comparator output. Loss of signal (neither mark or space frequency) will produce a loss of signal condition, which will cause the comparators to produce an output if the fault detectors are picked up. After 150 ms of signal loss, the logic will block the output to prevent a trip output. For an external fault, the local and remote inputs to the comparators will be out of phase and no output will be produced. If there is a loss of signal during the external fault, there will be output from the comparators and the relay will trip.

4.1.5.3 Segregated phase comparison unblocking

The segregated phase comparison system can be divided into two types: a two subsystem scheme and a three subsystem scheme. The two subsystem scheme operates from a delta current ($I_a - I_b$) for all multiphase faults and from a ground ($3I_0$) current subsystem for all ground faults. The three subsystem scheme has a subsystem for each phase (I_a , I_b , and I_c). Several unique features of this scheme are described by Sanders and Ray [B156].

The basic operation of the relay scheme is that each subsystem operates as a dual-phase comparison system which is described in 4.1.5.2. The two subsystem scheme would require two bidirectional FSK channels, and the three subsystem scheme would require three separate FSK channels. Continuous channel monitoring would be provided, because either a mark or a space carrier signal is always transmitted on each separate channel.

4.1.6 DTT

DTT, sometimes referred to as intertripping, describes the process of sending a trip signal from one substation to another. It differs from other carrier applications such as DCB or DCU in that, in most cases, the design is such that the remote terminal only needs the receipt of a proper DTT signal to trip.

DTT is often used to protect equipment such as transformers and circuit breakers. A common application involves a transformer tapped into a line with no high-side circuit breaker. The transformer relays trip the local breakers, and the remote end is tripped by the DTT function. DTT is also used for line protection, notably in DCB applications in which the DTT function may be used as a supplement to trip a weak terminal from the strong one.

The modulation technique is always FSK, with the standby mode usually called “guard,” and the shifted mode called “trip.” Channel times range from about 5 to 25 ms. Because fault detectors or other supervision may not be used, the equivalent of two transmitters at two different frequencies and two receivers (for illustration purposes designated A and B) can be used with the transmitters in parallel and the receivers in series for security or in parallel for dependability. In some schemes, a guard signal is required for a certain number of milliseconds before a trip is recognized.

A “shared channel” scheme is one that uses the DTT equipment for both direct tripping and for the line protection. For example, the A and B transmitters are both keyed by the direct trip relays but only the A transmitter by the line relays. At the remote terminal, receiver A may be used as the permissive input for the line relaying scheme and receivers A and B for the direct trips. When selecting equipment for a shared channel application, use the same criteria as would be used for the line protection, and select the same coordination delays.

4.1.7 Channel timing

4.1.7.1 Noise effects on coordination

The receiver circuit will filter out most noise, but occasionally a noise burst will come in near or at the trip frequency. To prevent this problem, the receiver may have some additional noise detector circuits.

Trip delay: In most frequency shift receivers, the trip frequency must be present for a predefined time before closing its output. This time delay may be fixed or adjustable depending on the circuit in the receiver. For DTT applications, the time may be set longer to add more security, whereas permissive tripping may not need the added time for security.

Bipolar noise detector: This circuit protects against signals that shift frequency from guard to trip and then back to guard, but not staying at trip frequency for the trip delay to activate. In this case, the bipolar noise detector adds more time to the trip delay to prevent misoperations.

Signal level: The receiver may have circuits to detect high or low signal levels to block tripping.

Refer to Clause 10.

4.1.7.2 Coordinating time delays and current reversal

Pilot relaying systems of the directional comparison type (i.e., DCB, DCU, and POTT) use status information from relays at both (or all) ends of a line in making a decision to trip. Information about the directional indication (forward or reverse) at the remote end of the line is communicated over the PLC channel and combined with local forward or reverse indication.

To ensure security in schemes of this type, coordinating time delays usually have to be provided to accommodate

- a) Possible differences in relay response times at the two ends of the line
- b) Time delay introduced by the PLC channel

For example, in a blocking scheme, the tripping function must be delayed a short time to ensure that any blocking signal from the remote end has time to arrive. As shown in the Figure 3, the tripping relay at A must be delayed to ensure that it does not trip for a fault in the next line section. The required delay X (as shown in Figure 3) is the sum of

- a) Maximum difference in the response time of the forward relay at A and the reverse relay at B $[B - A]$
- b) PLC channel time
- c) Plus a time margin

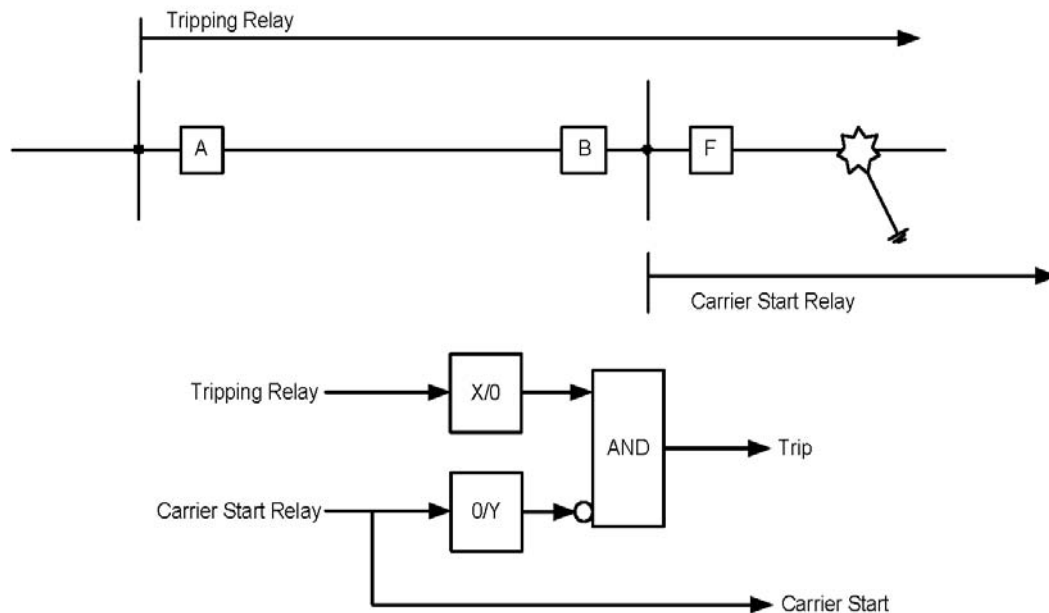


Figure 3—Blocking scheme time delay

Likewise, a reset-coordinating time delay Y (as shown in Figure 3) is required to be sure that, when breaker F opens to clear the external fault, the blocking signal received at A is not removed before the tripping relay at A resets. This coordinating delay usually takes the form of a signal extending timer that prolongs the blocking signal after the reset of the reverse-looking relay at B . The required signal extension time is

- Maximum difference in the reset time of the forward relay at A and the reverse relay at B [$A - B$]
- Minus the PLC channel dropout time
- Plus a time margin

It is difficult to evaluate the difference in relay operating and reset times without thorough testing under a wide variety of system and fault conditions. Manufacturers of relay systems generally provide guidance for setting of these coordination timers. In some relaying systems, particularly those using electromechanical relays, the required time delays have been built into the “carrier auxiliary” relays and are not intended to be user adjustable.

It is undesirable to set these coordinating timers any longer than is necessary. The pickup coordinating timer delays tripping for internal faults, and the reset coordinating timer may delay tripping for faults that evolve from external to internal, e.g., a fault involving the breaker B . Note that the inherent channel pickup delay *increases* the required setting of the pickup coordinating timer, whereas the channel dropout delay *decreases* the required setting of the reset coordinating timer.

Unblocking and permissive overreaching schemes do not require coordinating timers for the simple external fault coordination. The operating principle requires that both a received trip signal and a local forward relay operation be present before tripping can occur. For the external fault, relay A receives no trip permission and relay B sees a reverse fault, so there is no logic “race” that must be resolved.

Current Reversal: Another fault situation requiring timing coordination occurs when two protected lines run in parallel or substantially in parallel through short interconnecting lines. This situation is commonly referred to as current reversal. In Figure 4, a fault has occurred on line C–D near breaker D. Relay A can see the fault but is prevented from tripping because the directional information from the relay at breaker B indicates that the fault is in the reverse direction.

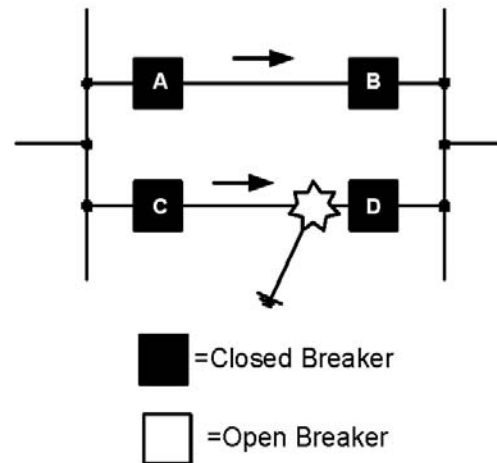


Figure 4—Setup for current reversal scenario

If the line A–B protection is a blocking scheme, then the relay at B sends a blocking signal to A to prevent tripping. Conversely, if the scheme is an unblocking or a permissive overreaching type, then B continues the normal guard signal to A, which indicates that A should not trip.

If breaker D should open before breaker C on the faulted line, the fault current in line A–B suddenly reverses direction as shown in Figure 5.

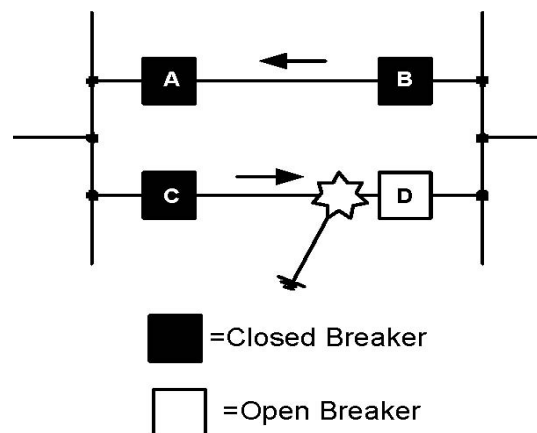


Figure 5—Current reversal occurrence

In a blocking scheme, relays at both A and B have a tendency to trip incorrectly during the current reversal, but they are prevented from doing so by the pickup and reset coordination timers. The pickup coordination timer at B prevents the forward-looking relay at B from tripping while waiting for the reverse-looking relay at A to send a blocking signal. Also, the reset timer at B continues transmission of a blocking signal to A long enough to permit the forward-looking relay at A to reset.

In a permissive overreaching or unblocking scheme, the initial fault near D will cause the forward-looking relay at A to send trip permission to B. When the current reverses, relay B will suddenly see a fault in its forward direction and time coordination is necessary to ensure that B does not trip before the permissive signal from A can be removed. The simplest solution to this race is a pickup timer for the forward-reaching relay, just like that described for the blocking scheme. The required timing for this timer is the sum of

- a) The difference between the reset time of relay A and the pickup time of relay B $[A - B]$
- b) The channel dropout time
- c) Plus a time margin

Because the permissive and unblocking schemes do not require a pickup delay unless a current reversal is about to occur, more sophisticated logic is often employed that inserts the pickup delay timer only when current reversal conditions are anticipated. This process avoids the tripping delay that may otherwise be experienced while the pickup timer is timing out for a normal internal fault. Imminent current reversal can be sensed by receipt of trip permission with no forward relay pickup or by operation of a reverse-looking relay function provided for that purpose.

4.1.7.3 Channel delays when using phase comparison or current differential systems

Proper operation of phase comparison equipment requires both phase and symmetry alignment between the local and the remote comparison quantities. Phase alignment is related to the absolute channel time between the remote relay and the local one. Symmetry alignment compensates for the channel time variation between the receiver detecting a transition from the low-frequency state to the high-frequency state under frequency shift transmission schemes, or from the OFF-ON state versus the ON-OFF state for schemes using ON-OFF keying.

Adjustment of the phase and symmetry requires injection of test currents that are in phase with one another. Assuming that the relay comparison network is operating properly, the use of a single phase-to-ground current will provide a suitable source for adjustment. Some possible methods are described in 10.1.3.

4.2 Telemetry applications

Telemetry applications include monitoring of voltage, current, watts, vars, and so on. Telemetry information is a relatively slow analog and does not require a high-speed data rate. As a result, a narrowband PLC channel can be used for this function.

An early form of telemetry uses the pulse duration with the ON-OFF carrier (AM); the analog signal is transmitted for a given duration. The length of the duration corresponds to a given analog level. This form of telemetry takes time and is suitable for slow changing levels.

Later forms of telemetry use FSK to transmit information. A frequency within a narrow bandwidth is shifted to convey the analog level to the remote. Analog level changes can be conveyed much faster than in the pulse duration method.

Most telemetry information is performed by converting the analog signal into binary information that is used to shift the FSK frequency high and low. This result may be accomplished by either using a narrowband FSK tone, which is then used to modulate a single side-band (SSB) PLC, or using a dedicated narrowband set.

4.3 Voice applications

Voice communications can be imposed over the PLC using AM. An ON–OFF transceiver in a half-duplex mode or an FSK transceiver in a full-duplex mode may be used. A narrow bandwidth (3 kHz or more) around a center frequency will allow for normal speech recognition. The disadvantage is that voice communication requires a greater signal-to-noise ratio (SNR) and bandwidth than other carrier applications.

Voice continues to be used in SSB systems. On SSB systems, the voice bandwidth may be limited to as low as 2000 Hz.

5. Power-line channel considerations

Application of a PLC system for a communications channel considers the types of channels available, the transmitter–receiver equipment characteristics, and the reliability and quality of performance required. An adequate transmission path must be furnished under both varying system configuration and adverse weather conditions. Preliminary application studies of a PLC system should evaluate the trapping and coupling requirements, the carrier channel loss, the noise level at the receiver, the effect of weather on losses and noise, the calculation of signal-to-noise ratio (SNR), and frequency spacing requirements.

5.1 Line characteristics

5.1.1 Characteristic impedance

The characteristic impedance [B71] of a transmission line (sometimes called surge impedance) is defined as the ratio between the voltage and the current of the traveling wave on a line of infinite length. This ratio of voltage to its corresponding current at any point in the line is a constant impedance, Z_0 . It is a function of the per-unit length series resistance, series inductance, shunt capacitance, and shunt conductance of the line, and it is independent of line length. The constant characteristic impedance of a two-wire line can be expressed as

$$Z_0 = \frac{V_+}{I_+} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \quad (1)$$

where

- R is the resistance per unit length, in ohms
- L is the inductance per unit length, in henrys
- G is the shunt conductance per unit length, in mhos (siemens)
- C is the shunt capacitance per unit length, in farads
- $\omega = 2\pi f$ f is the frequency in Hertz

In practice, at PLC frequencies, the quantities $j\omega L$ and $j\omega C$ are large by comparison with R and G , so that the latter can be neglected, and the expression for characteristic impedance can be reduced to

$$Z_0 = \sqrt{\frac{L}{C}} \quad (2)$$

By applying conventional formulas for L and C to Equation (2),

$$Z_0 = 276 \log \frac{D}{R} \text{ for } \frac{D}{R} \geq 20 \quad (3)$$

is obtained, where D is the distance between conductors and r is their radius in the same units. Equation (3) expresses the characteristic impedance of a line consisting of two aerial wires. For a single aerial conductor at a height h aboveground and radius r , the characteristic impedance is

$$Z_0 = 138 \log \frac{2h}{r} \quad (4)$$

For bundled conductors, the geometric mean radius (GMR) is used for r in Equation (3) and Equation (4). The GMR is defined in Figure 6 for three arrangements, where GMR_c is the GMR of a single conductor.

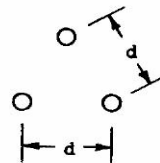
TWO-WIRE BUNDLES

$$\text{GMR} = \sqrt{\text{GMR}_c \cdot d}$$



THREE-WIRE BUNDLES

$$\text{GMR} = \sqrt[3]{\text{GMR}_c \cdot d^2}$$



FOUR-WIRE BUNDLES

$$\text{GMR} = \sqrt[4]{\text{GMR}_c \cdot \sqrt{2} d^3}$$

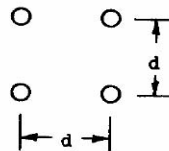


Figure 6—GMR of conductor bundles

In the case of a three-phase transmission line, the calculation of the characteristic impedance is more involved and is further complicated by the use of bundled conductors. If a transmission line is terminated in its characteristic impedance, no energy will be reflected from the termination, and the sending-end behavior is the same as though the line was infinitely long.

An impedance network of six impedances, as shown in Figure 7, is required to terminate a three-phase line in its characteristic impedance. Because a transmission line is seldom, if ever, terminated in its characteristic impedance network, the impedance observed by a set of coupling equipment connected to the transmission line, either phase-to-phase or phase-to-ground, will be affected by reflected energy on the uncoupled phases.

Another and more practical value frequently called characteristic impedance is the value of the impedance to which the carrier coupling equipment is matched to obtain minimum mismatch and thus achieve maximum power transfer. This value of characteristic impedance is affected by the terminating impedance of the phase(s) not used in the coupling circuit. Measurements indicate that for phase-to-phase coupling, as the terminating impedance of the uncoupled phases varies from an open circuit to a short circuit, the characteristic impedance varies slightly. However, much larger differences occur for phase-to-ground coupling.

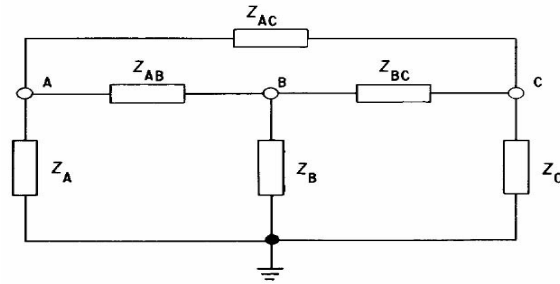


Figure 7—Terminating network for a three-phase line

As shown in Equation (3), the characteristic impedance is based on the radius of the conductors and the distance between conductors. In general, both dimensions increase with higher voltages so that the ratio remains nearly the same. Therefore, there is very little difference in the characteristic impedances of lines of various voltages as long as only one conductor is used for each phase. Lower values of characteristic impedance will exist on extra-high-voltage (EHV) transmission lines where bundled conductors are used with an effective radius that is much larger than the radius of a single conductor. Table 1 shows the range of values that can be expected from a wide variety of lines.

Table 1—Range of characteristic impedances for PLC circuits on overhead lines

Transmission line conductor (each phase)	Characteristic impedance in Ω (phase-to-ground)	Characteristic impedance in Ω (phase-to-phase)
Single wire	350–500	650–800
Bundled (two-wire)	250–400	500–600
Bundled (four-wire)	200–350	420–500

The values of the characteristic impedance of power cables vary greatly from those for overhead lines, and there is also a large variation among different types of cables. In general, there has not been much information published on power cables, such as the high-frequency characteristic impedance, and it may be required to perform measurements on the actual cable used for a particular circuit. Generally the characteristic impedance of a power cable will be between 10 Ω and 60 Ω .

5.2 Channel losses

5.2.1 Losses

The loss in power as a signal travels through the various components and media of a transmission system is best measured in decibels, which allows the losses to be added to arrive at a total loss for the system without regard to the change in impedance in the system. The loss in decibels is defined as follows:

$$\text{LOSS} = 10 \log \frac{P_1}{P_2} \quad (5)$$

$$\text{LOSS} = 20 \log \frac{V_1}{V_2} \quad (6)$$

$$\text{LOSS} = 20 \log \frac{I_1}{I_2} \quad (7)$$

where P is power, V is voltage, and I is current and the subscripts indicate points of measurement in the channel. Equation (6) and Equation (7) are valid only if the circuit impedances are equal at the points where the measurements are made. The assumption that a junction represents a particular impedance, such as a 50 Ω coaxial connection to a coupling device will lead to an erroneous result. The only valid measurement made in a system is across a resistive load of known value, which can only be made at the output of a part of the system or at the input to a device with the device removed and replaced with its nominal input impedance.

The total attenuation of a PLC communications channel consists of series and shunt losses. The series losses can take the form of coupling components such as impedance matching transformers, RF symmetrical and skewed hybrids, series L/C circuits used for isolating transmitters, various filters, line tuners, and coupling capacitors. Other series losses include the resistive losses of the transmission line. The line losses are usually lumped together, including the series and shunt losses of the transmission line, and are called line loss. Other series losses may include the mismatch losses of an overhead line/power cable junction as well as the losses incurred from not matching the various components of the circuit perfectly at impedance change points.

Shunt losses may include line trap losses, tap line losses, bypass losses (which may include series losses from line tuners and other coupling components), and effects from the number of lines on the bus side of an isolating line trap as well as the station capacitance. On cable circuits, the series losses are critical because of the low characteristic impedance of the cable relative to resistive losses in other components, including coupling capacitors.

5.2.2 Attenuation in overhead lines

At PLC frequencies, a typical power line operates as a transmission line that is long compared with the wavelength of the signal frequency. The performance of such a line can be predicted with reasonable accuracy by applying modal theory, provided that all relevant parameters are known and a suitable computer program is available to the application engineer. For some applications on short lines, adequate performance predictions can be made based on attenuation measurements made on similar lines.

Three basic methods are used to determine this loss. These will be discussed in a later section. The line loss in this does not include any losses from external influences. The losses relate to the characteristics and parameters of the line. The line loss is primarily a function of the following parameters:

- Transmitter frequency
- Type of line construction
- Line geometry
- Phase conductor size, material, surface, condition, etc.
- Ground wire size, material, location, etc.
- Method of coupling
- Type and location of transpositions
- Weather conditions
- Ground conductivity
- Insulator leakage

The loss in an overhead transmission line increases with increasing frequency because of increasing radiation losses, conductor losses, dielectric losses, and coupling to the ground wire, to the ground and to towers, and to other lines in the vicinity. The losses may be reduced by using smaller phase-wire spacing-to-height ratios and higher conductivity materials in the phase wires. The line voltage dictates the spacing and

height of the phase wires, the effective phase wire cross section, and the number of conductors per phase. Because of the use of larger phase conductors and increasing number of phase conductors per phase, HV transmission lines exhibit decreasing loss with increasing voltage.

For economical reasons, the conductor and ground wires used in power line construction are made of different materials. The phase conductors are usually made of a stranded steel core covered with stranded aluminum outer conductors. The losses at carrier frequencies depend on the composition of the conductors and their resistive and reactive characteristics. Some circuits may use different conductor sizes between stations when different line geometries are used.

The loss in the ground wires is especially important in single phase-to-ground coupling. The ground wires may also be of stranded steel and aluminum conductors or of stranded steel. The losses in the ground wires will influence the line losses for low-loss modes near the coupling locations. The coupling method will influence the losses in the line. Center-phase-to-ground is usually used on horizontally constructed lines for noncritical application for protection channels. For more critical applications, where it is important to receive a signal under fault conditions, for severe weather conditions, or for long lines with higher losses, a phase-to-phase or three-phase coupling method may be used to improve received signal strength or margin. The multiphase coupling method may revert to a phase-to-ground or a phase-to-phase coupling under fault conditions and assure that a protection signal will be received under conditions when signal reception is most critical. Line-to-line coupling methods are also used to increase redundancy on double circuit lines for horizontal or vertical lines. Coupling to the phase wire, which assumes the physical center position for the longest distance, will usually result in the lowest line loss for phase-to-ground coupling.

Transpositions in long transmission lines will increase the losses compared with nontransposed lines. A single transposition in a very long line can result in 6 dB of added loss. The loss is usually not that severe, especially on lines with multiple transpositions, and on short lines. Three transpositions will generally allow the phase conductor to resume their original positions and usually give lower losses than an even number of transpositions.

Weather conditions can introduce additional losses that are also a function of the frequency of the signals on the line. Hoar frost forming on the line may increase the losses by factors of 4 to 5 over the fair weather losses on the line. Ice on the conductors has relatively the same effect, except that the high-frequency effect is more severe. Lines that are subject to icing, frost, or heavy rains should use the lowest frequencies, and multiphase coupling should be considered to increase margins to acceptable magnitudes during times of extreme weather conditions. The existence of dirty insulators in some metropolitan areas where fly-ash deposits are severe can influence line losses in foul weather.

Poor ground conductivity can add to line losses when the return path is through the ground, as in phase-to-ground coupling schemes, which is especially true in areas where the soil is dry and sandy. The soil acts as a very good insulator, and the preparation of the ground mat at the substations to enhance the conductivity at the coupling locations is important to reduce line losses. The mat must extend along the line for several spans to reduce the coupling losses caused by the soil conditions.

5.2.3 Attenuation in power cables

The losses in power cables are greater than those in overhead line circuits. The specific type of cable including the conductor size, material and number of skid wires, type of insulation material, diameter, and voltage rating will influence the cable loss characteristic. The manufacturer may supply this data as well as the RF characteristic impedance and attenuation. Most data available on power cables have been accumulated by users, because the characteristics of the cables are basically related to the transfer of power at 50 Hz or 60 Hz and are not concerned with RF characteristics.

Power cables with cross-bonded sheaths are not suitable for use at PLC frequencies. The losses of a typical power cable for 138 kV use is shown in Figure 8. The losses per kilometer show that long cable circuits (in excess of 16 km) are not usable for PLC circuits. Most PLC circuits on power cable installations are confined to the frequency range below 100 kHz, with the majority being below 60 kHz. New insulating materials used in lower voltage distribution cables may reduce the losses in higher voltage cables and result in higher characteristic impedances.

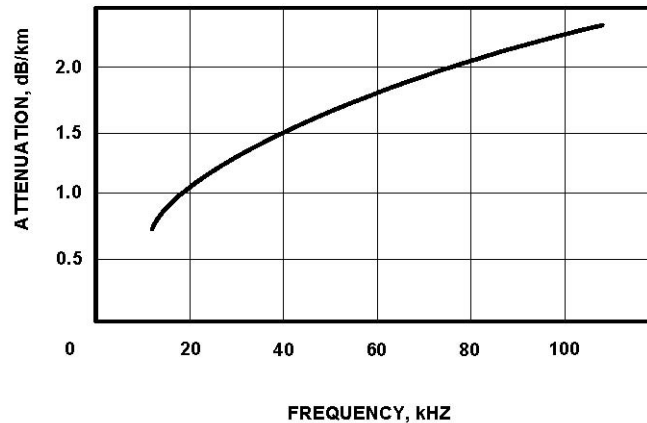


Figure 8—Typical losses for a 138 kV power cable

Most underground power cable installations are single-conductor, self-contained, single- or three-phase cables. Experimental work on cryogenic cables may result in lower loss cables. Single-conductor, self-contained cables use a hollow oil-filled conductor and an oil-impregnated paper insulation. An extruded metal shield encases the insulation and conductor. The pipe-type cable uses a solid conductor with oil-impregnated paper insulation wrapped with synthetic tape layers and thin metallic tapes. One or three conductors are housed in a pipe that is filled with high-pressure oil or gas. The fluid may be pumped through the pipe to ensure a more even temperature under varying loading conditions, and the fluid will undergo cooling to remove the heat caused by losses in the system. Protective skid wires are wrapped around the conductor or conductors for protection during insertion in the pipe. Skid wire conductivity affects the HF attenuation. The characteristic impedance of power cables varies from 10 Ω to 60 Ω .

Representative values of attenuation on a 138 kV power cable are shown in Figure 8 for single-phase-to-ground coupling. Coupling in a three-phase cable for phase-to-phase insertion gives significantly lower losses than for single-phase-to-ground coupling. Most power cable installations are for single-phase cables. The modal coupling induced in overhead lines does not occur in single-phase power cables, and no advantage, except for redundancy, is gained by using multiphase coupling as was true for overhead line applications. The noise characteristics of power cables are superior to overhead lines because the conductors are not exposed to the weather or to other external influences.

5.2.4 Attenuation at discontinuities

The impedance looking into a short line not terminated in its characteristic impedance will vary depending on the mismatch at the load and the attenuation of the line. This variation is caused by reflections at the load that affect the impedance looking into the input of the line. It may be impossible to match a transmitter to the impedance of the line. When several transmitters are connected to this line, the variation in the impedance will give varying reflected power percentages for each transmitter and result in an unsatisfactory coupling and tuning circuit. This situation may be improved if the distance to the mismatch is known, and the frequencies may be selected to fall in between the maximum and minimum reflected impedances caused by the mismatch. Any change in the line could result in a change in the input impedance presented to the coupling equipment and result in unacceptable reflection of power. Where there is substantial loss between the insertion point and the location of the mismatch, the only loss sustained is the loss of the mismatch. The

loss from an impedance discontinuity or a mismatch between a line of characteristic impedance Z_0 and a load of Z_1 is given in decibels by

$$\text{dB}_{\text{LOSS}} = 20 \log \left[\frac{Z_0 + Z_1}{2 \sqrt{Z_0 Z_1}} \right] \quad (8)$$

This type of loss is common when an overhead line and a power cable form a junction without impedance matching at PLC frequencies.

The other type of discontinuity encountered on some overhead transmission lines is an untrapped stub line. An open stub line will reflect a low impedance at PLC frequencies, which are an odd number of quarter-wavelengths at the connection point. The open stub may be represented by a lightly loaded tap. This situation may result in complete frequency-dependent shorting of the main line at several PLC transmitter frequencies. The length of the stub line should be investigated to determine if the line length corresponds to a frequency being used on the main line. A stub line that is shorted will reflect a short-circuit impedance at all frequencies that are an even number of quarter-wavelengths at the connection point. A shorted stub may be represented by a heavily loaded tap or an overhead line terminated in a power cable. Either situation will result in no signal transmission past the connection point of the stub at the critical frequencies.

The solution to either situation is to install a line trap on the stub line where it is connected to the main line. Frequency selection, where taps are connected without line traps, can best be done by actually measuring the line and the coupling characteristic of the line. Wide-band line tuners are usually required. A line with multiple taps without traps represents a formidable challenge to couple multiple frequencies without end-to-end measurements. Any change in the circuit may disturb the impedance characteristics looking into either end.

5.2.5 Coupling losses

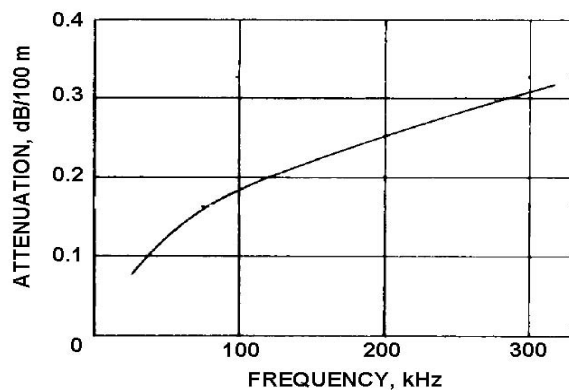
Coupling losses include all losses involved in the isolation and tuning equipment at both ends of the PLC installation between an individual transmitter and its companion receiver. These losses include hybrid and filter losses associated with the coupling circuit. Also included are cable, line tuner, coupling capacitor, and line trap losses. Mismatch losses caused by improper selection of IMT taps are also part of coupling losses.

5.2.5.1 Carrier frequency separation equipment

Several transmitters and receivers on a common coupling circuit require isolation elements to prevent signal absorption, interference, and intermodulation. Because all signals must be routed into one or two coaxial cables depending on the number of inputs to the line tuner, some type of combining or separation equipment must be present if more than one transmitter or receiver is used at a PLC terminal. These separation elements usually take the form of hybrids and various filter circuits. The filters may be simple series or parallel L/C units, more complex bandpass filters, or high-pass/low-pass branching filters. The loss of the individual elements varies with the type of element. Values of loss must be obtained from the manufacturer. Typical values are shown in Table 2 for some commonly used isolation elements.

5.2.5.2 Coaxial cable

Interconnections among the various transmitters, receivers, and isolation elements are usually made with RF coaxial cables. The length of these interconnections are short and can generally be ignored. The connection from the combined equipment to the line tuner requires a coaxial cable. The common type of cable, RG-8/U, has an attenuation characteristic that varies with frequency and is shown in Figure 9.

**Figure 9—Attenuation characteristic of RG-8/U****Table 2—Attenuation of isolation elements**

Separation equipment	Attenuation (dB)
Balanced hybrid	3.5
Skewed hybrid	
Transmit path	0.5
Receive path	12.0
L/C unit	1.0–3.0
Bandpass filter	0.5–2.5
Low-pass/high-pass filter	1.0

5.2.5.3 Line tuner losses

Line tuner losses are related to the number of tuning elements in the device, the tuning frequency, the impedance of the line or power cable, and the value of the coupling capacitor. The values vary widely with the application and can be requested from the manufacturer for a particular design. Losses may vary from 0.2 dB to 2 dB. More complex tuners will generally have higher losses than a simple resonant tuner. The bandwidth of the line tuner is the primary determiner of the losses.

5.2.5.4 Coupling capacitor losses

A high dissipation factor in a coupling capacitor may produce an effective series resistance of several ohms and can contribute to the coupling losses in the channel. For overhead lines, this added series resistance will usually represent a very small portion of the losses in the coupling circuit and can generally be ignored or lumped in with the line tuner losses. For power cables, this added series resistance will contribute a significant loss in the form of I^2R losses to the coupling circuit. The contribution of the coupling capacitor to the coupling losses can add several decibels of loss to power cable coupling losses. The contribution is more severe as the characteristic impedance of the cable is reduced. The temperature behavior of the coupling capacitor value can contribute to the coupling losses by detuning the line tuner for wide temperature variations. Figure 10 shows a curve relating the behavior of a coupling capacitance with

temperature. For cable circuits where the bandwidth is very narrow and for line tuners resonated at low PLC frequencies below 60 kHz with low values of coupling capacitance, the tuning is very selective and variations in the capacitance can cause appreciable changes in the tuning of the series resonant circuit containing the coupling capacitor.

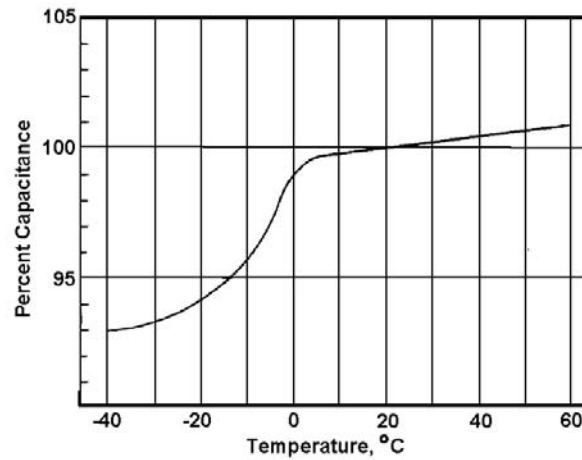


Figure 10—Coupling capacitor capacitance versus temperature

The insulation systems of modern coupling capacitors are less prone to large temperature variations in capacitance and exhibit lower dissipation factors than older designs. Also, higher values of capacitance are available at higher voltages, which will increase tuner bandwidths. Extra high capacitance coupling capacitors should be considered for power cable coupling circuits to reduce selectivity problems with low-frequency coupling circuits.

5.2.5.5 Shunt losses

Shunt coupling losses occur at the coupling locations and are primarily the result of losses caused by line traps and drain coils in the coupling capacitor or in the line tuner and are usually lumped with these elements of the coupling circuit. The sneak paths to ground caused by improper insulation of the lead-ins to coupling capacitors and aging coaxial cables are also examples of shunt losses. The leakage currents can be inductive, resistive, or capacitive. Proper treatment of lead-ins using adequate insulators can reduce these effects to negligible values. The line trap represents a fixed loss depending on the blocking impedance at the frequency used. The capacitance of the bus also contributes to the shunt loss caused by the line trap. Other lines connected to a bus can also reduce the bus impedance and increase the effective loss of the coupling circuit.

For a known value of shunt impedance, the shunt loss can be calculated using

$$\text{dB}_{\text{LOSS}} = 10 \log \left| \frac{Z + Z_S}{Z_S} \right| \quad (9)$$

where

Z is the nominal circuit impedance

Z_S is the shunt impedance

5.3 Line loss calculations

5.3.1 General

The calculation of line losses can be done with the aid of tables and graphs of typical lines. This method is referred to as the “graphical method.” The results are usually very conservative. The second technique involves the use of restricted formulas and assumptions and is referred to as “simplified modal analysis.” This method requires either a computer or a programmable calculator to make efficient calculations. The lines analyzed using the second approach must be horizontally constructed ac lines. This method will give results closer to actual measurements for most applications. However, it cannot predict the existence of singularities caused by cancellations in some coupling schemes. The third method involves a physical analysis of the line(s) and generally puts no restrictions on the construction or parameters of the line. These programs can usually make calculations for ac well as dc HV lines, multiple lines, and do fault analysis and show temperature and weather effects. Tower dimensions, conductor dimensions and characteristics, ground wires and ground resistivity, transpositions, and so on are considered. This method will give line-loss data very close to the actual measured losses when coupling losses are considered.

The development of EHV transmission lines with transpositions has created new problems for the PLC communications engineer. The short lines of the past have been replaced with long lines where the actual losses in the line are important to design the PLC system with adequate SNR and margin. The received signal levels on short lines did not present a challenge to the communication engineer because there was adequate margin if the coupling circuits were properly designed and maintained. The construction of EHV lines required a more accurate method of obtaining and predicting the line losses before the actual construction. Modal analysis is a mathematical tool that provides a more accurate method of calculating PLC propagation, much like symmetrical component analysis can be used for predicting the response of three-phase systems. Modal analysis is not only a mathematical tool, but it can be readily identified in the physical world.

5.3.2 Graphical analysis

The graphical method makes use of a graph that represents the losses of a nominal HV line at 138 kV in the frequency range from 30 kHz to 300 kHz. The technique requires that the user plug in values from three tables representing the line voltage multipliers, considerations for the coupling method and the type of shield wires, and for transpositions. Figure 11 and Table 3, Table 4, and Table 5 give these parameters. There are fair weather multipliers as well as foul weather values for the attenuation curve. The change in losses because of foul weather conditions are not consistent from one voltage to the next. The information presented here is based on many years of experience and cumulative data collections by many individuals.

5.3.3 Simplified modal analysis

The essential assumptions for simplified modal analysis are the following:

- a) Only one three-phase line in a horizontal plane is considered.
- b) Surge impedances are the same for all phases.
- c) The forms of the basic current modes are independent of frequency.
- d) Instantaneous currents flowing in the three phase wires are either in phase or 180 degrees out of phase.

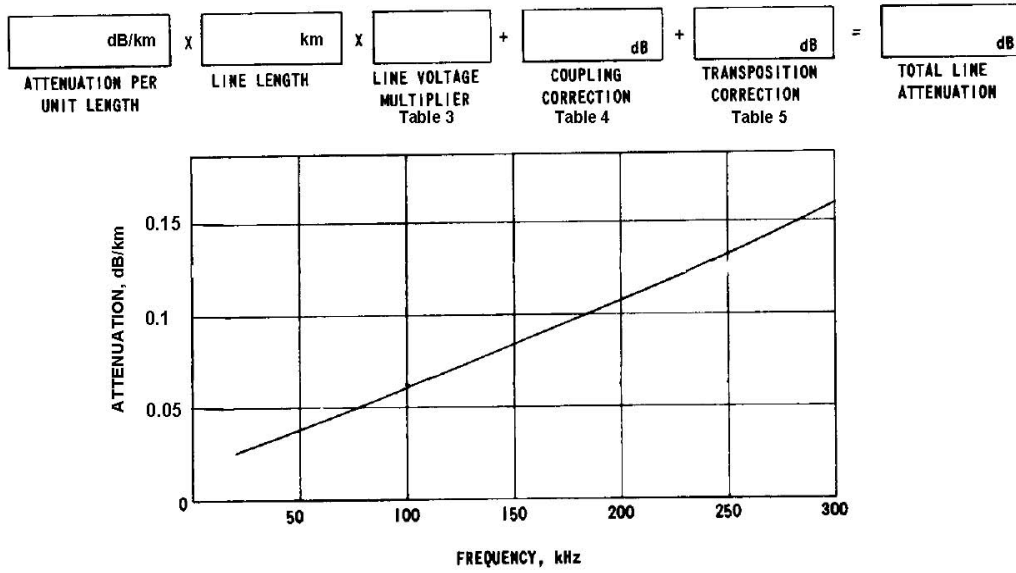


Figure 11—Line attenuation graph for graphical method

Table 3—Line-voltage multipliers

Line voltage (kV)	Fair weather	Adverse weather ^a
34.5	1.46	2.19
69	1.20	1.80
115	1.11	1.66
138	1.00	1.50
230	0.78	0.98
345	0.72	0.90
500	0.54	0.68
765	0.50	0.63

^aUnder certain severe frost conditions, extreme losses can occur.

Table 4—Coupling correction factors

Type of coupling/shield wires	Correction (dB)		
	<8 km ^a	>80 km ^a	>240 km ^a
Mode 1 coupling	0	−2	-
Center to phase to outer phase	0	0	-
Center phase-to-ground			
Al or Cu wire	0	1	-
Steel wire	1	4	-
No shield wire ^b	8	8	-
Outer phase-to-ground			
Al or Cu wire	0	-	13
Steel wire	1	-	15
No shield wire ^b	19	-	19

^aLinear interpolation should be used to determine loss between limits of line length.^bSubject to wide variations.**Table 5—Transposition corrections^a**

Transposition	Correction (dB)	
	<16 km ^b	>160 km ^b
1	0	6
2–4	0	8
5 or more	0	10

^aApply for 345 kV and higher.^bLinear interpolation should be used to determine loss between limits of line length.

The analysis allows for three current modes to be propagated down the line. These consist of a low-loss mode, a medium loss mode, and a high loss mode. Mode 1 is the low-loss mode and consists of currents of equal magnitude flowing in an outward direction in the outside phase wires and a current of twice this magnitude flowing inward in the center phase wire. The medium loss mode is Mode 2 and has two currents of equal magnitude but of opposite phase flowing in the outer phase wires. The loss in this mode is one tenth of the high loss mode. Mode 3 is the high loss mode with currents of equal magnitude flowing outward in all three phase wires and returning through the ground. This mode quickly dissipates because of the loss in the ground. The typical losses of these modes are shown in Figure 12.

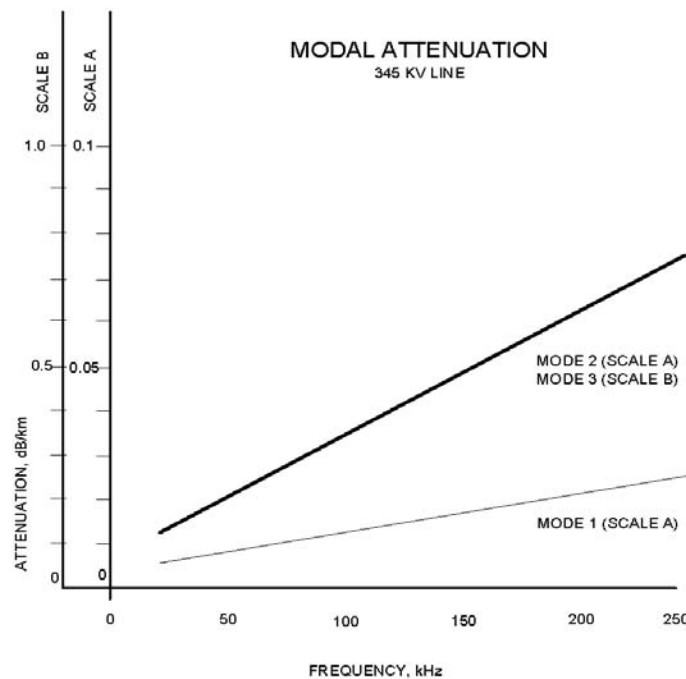


Figure 12—Typical losses of Mode 1, Mode 2, and Mode 3

The details of the simplified modal analysis are given in Sanders and Ray [B156] and the *Relaying Communications Channels Application Guide* [B151]. The currents injected into the power line by the coupling circuit are distributed into the three assumed modes. A center phase-to-ground coupling will generate Mode 1 and Mode 3 components, of which two thirds of the power is in the low-loss mode 1 component. A center phase to outer phase coupling will result in Mode 2 and Mode 1 components only. One fourth of the power is in the medium loss Mode 2 components, whereas three quarters of the power resides in the low-loss Mode 1 components. Coupling to an outside phase results in all three modes being created with one third of the power in Mode 3, one half in Mode 2, and only one sixth in Mode 1. This power distribution shows a comparison of the losses expected for these types of coupling. Coupling to all three phases will give only a Mode 1 distribution in a line with no transpositions. If the coupling is only to the outside phase wires, only Mode 2 will be created on an untransposed line. To some extent, this explains the high line losses for dual outer phase coupling. These coupling schemes are described in more detail in 5.8.

The behavior of the modal currents at a transposition considers the magnitude and direction of the currents after these currents have been attenuated by the line up to the transposition. The currents essentially redistribute according to the relations for this analysis. All three modes are usually present after a transposition because currents are usually present in all three phase wires. The high loss mode will be quickly dissipated, and only Mode 1 and Mode 2 will remain at the next transposition.

At the end of the line, although there are currents in all three phase wires, useful power can only be extracted on the phase wires actually coupled. The concept of conversion is used to measure the efficiency of different coupling schemes. This relates to the ratio of the amount of power into the line to the Mode 1 power out of the line.

5.3.3.1 Simplified modal analysis calculations

5.3.3.1.1 Description

The following relation gives the propagation of electromagnetic energy on a single-conductor line, provided no reflections exist:

$$V_x = V_S e^{-\gamma x} \quad (10)$$

$$I_x = \frac{V_x}{Z_0} \quad (11)$$

where

- V_S is the sending-end voltage
- Z_0 is the characteristic impedance
- x is the distance from sending end, in kilometers
- V_x, I_x is the voltage and current at distance x from sending end
- γ is the propagation constant

The propagation constant is composed of two quantities

$$\gamma = \alpha + j\beta \quad (12)$$

where α is an attenuation constant in nepers per kilometer and β is a phase constant in radians per kilometer (1 neper = 8.686 dB.) The propagation constant is dependent on the physical properties of the conductor used plus its geometry with respect to ground.

It has been observed that if carrier energy is applied to a single conductor of a multiconductor line, then the propagation along the line does not follow Equation (12). Instead, the propagation of energy on the line depends on the number of conductors and usually involves all of them. Analysis of a multiconductor line shows that several modes of energy propagation may take place simultaneously. It can also be shown that the number of natural modes of propagation on a multiconductor line is equal to the number of conductors involved in the propagation of energy. The analysis of the multiconductor line is accomplished using a matrix equation

$$[V] = [V_S] e^{-[\gamma_m]x} \quad (13)$$

where m is an arbitrary integer to identify the modes. The solution of the Equation (13) will yield the voltage and current relationship of the modes. Each mode has its propagation constant and characteristic impedance, and each mode propagates in a manner that is independent of the other modes. The voltage and current at any location on any one conductor is the vector sum of the individual mode voltages and currents existing on that conductor at the particular distance x from the transmitter.

The remainder of the discussion will deal with the specific case of a single-circuit three-phase line of flat construction. This is a common type of construction for EHV circuits as well as for many lower voltage transmission lines. A typical example is shown in Figure 13. The assumption is also made that the shield wires are grounded at each tower and are at constant potential along their length. Thus, they do not generate any transmission modes. Based on this assumption, there are three natural modes of propagation, which will be labeled Mode 1, Mode 2, and Mode 3. Each mode has its propagation constant (γ_1, γ_2 , and γ_3) and characteristic impedance (Z_{01}, Z_{02} , and Z_{03}). Other transmission-line configurations, such as vertical or

triangular ac lines, dc lines, or power cables, will each have its set of modal parameters. The modal properties described in the following paragraphs are not appropriate for any except the general arrangement shown in Figure 13.

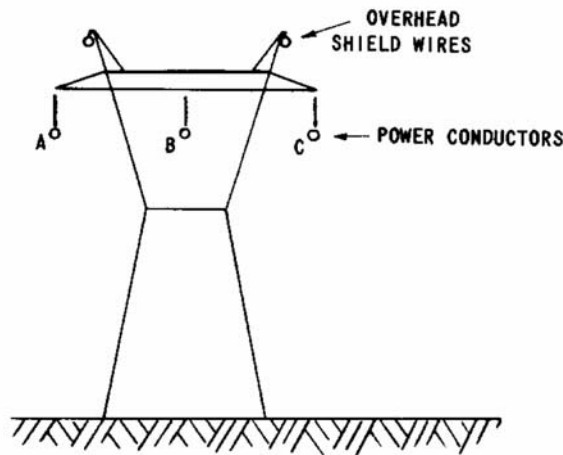


Figure 13—Typical single-circuit line construction

Mode 1⁶ is the least attenuated of the three modes and makes long-distance carrier communications possible. It nominally has current flowing out the two outer phases and returning via the center phase. Mode 1 attenuation is not only low, but it is also reasonably independent of frequency throughout the PLC range.

Mode 2 has its current flowing out on one outside phase and returning on the other outside phase. No Mode 2 current exists in the center phase. Mode 2 losses are greater than those of Mode 1, and its losses are more dependent on frequency.

Mode 3 propagates current almost equally on all three phases and has a ground return. This mode has such a high rate of attenuation that it may be neglected beyond a short distance (approximately 16 km) from the transmitter.

The vector relationships of modal currents (or voltages) in the three phase conductors are shown in Figure 14. Current (and voltage) distributions among the phase conductors are given in Table 6. These quantities are normalized to the phase A quantities. The factors p and q depend on the line under study. The factor p can range from about -1.6 to -2.0 , and q will have a range of about 1.1 to 1.3 .

Phase	Mode 3	Mode 2	Mode 1
a	$\xrightarrow{1}$	$\xrightarrow{1}$	$\xrightarrow{1}$
b	$\xrightarrow{q}$		$\xleftarrow{p}$
c	$\xrightarrow{1}$	$\xrightarrow{-1}$	$\xrightarrow{1}$

Figure 14—Modal vector relationships

⁶In some literature the lowest loss mode has been identified as Mode 3. The definition given here, which identifies Mode 1 as the lowest loss mode, is in agreement with earlier IEEE publications and with current practice in most parts of the world.

Table 6—Phase distribution of modal current and voltage

Phase	Mode 1	Mode 2	Mode 3
A	1	1	1
B	p	0	q
C	1	−1	1

As stated before, each mode has an independent propagation constant. Based on several examples of experimental data taken for lines from 345 kV to 765 kV, the general range for the values of attenuation and the relative phase velocity (which is dependent on the phase constant β) are shown in Table 7 and Figure 12.

Table 7—Attenuation and relative phase velocity for Mode 1, Mode 2, and Mode 3

Quantity	Mode 1	Mode 2	Mode 3
Attenuation (dB/km)			
At 30 kHz	0.006–0.0018	0.0054–0.06	
At 100 kHz			0.9–1.8
At 300 kHz	0.042–0.054	0.24–0.3	
Relative phase velocity	1.0	0.98–0.995	0.9

The attenuation constant ranges for Mode 1 and Mode 2 are given for frequencies of 30 kHz and 300 kHz. The attenuation can be expected to vary in almost a linear fashion between these two frequencies. The phase constant is represented for the relative propagation velocity with respect to the velocity of Mode 1, which is nearly the speed of light in free space.

These general ranges can be used to calculate line attenuation, keeping in mind that the modal quantities add vectorally to produce the phase quantities.

5.3.3.1.2 Coupling to the power line

When a carrier transmitter is coupled to the power line, it is usually done using single-phase-to-ground or a form of phase-to-phase coupling. All of the generally used methods of coupling generate different portions of Mode 1, Mode 2, and Mode 3 power. Because Mode 1 is the least attenuated, then it is desirable to generate as much Mode 1 as possible.

At the coupling terminal, the phase voltages and currents are set by the coupling configuration and are known. The mode currents generated must satisfy these boundary conditions. They can be calculated by solving

$$I_a = I_{a1} + I_{a2} + I_{a3} \quad (14)$$

$$I_b = pI_{a1} + qI_{a3} \quad (15)$$

$$I_c = I_{a1} - I_{a2} + I_{a3} \quad (16)$$

If voltages are used, V is substituted for I in Equation (14), Equation (15), and Equation (16).

When the magnitudes of I_{a1} , I_{a2} , and I_{a3} have been calculated, the modal power at the transmitter can be found. P_T is equal to the total transmitter power less the losses in the coupling equipment

$$P_T = P_1 + P_2 + P_3 \quad (17)$$

where P_1 , P_2 , and P_3 are the powers of Mode 1, Mode 2, and Mode 3, respectively

$$P_1 = \frac{(1 + p^2 + 1)I_{a1}^2}{Z_{01}} \quad (18)$$

$$P_2 = \frac{2I_{a2}^2}{Z_{02}} \quad (19)$$

$$P_3 = \frac{(1 + q^2 + 1)I_{a3}^2}{Z_{03}} \quad (20)$$

Now that the modal powers are known, the modal coupling efficiency can be calculated as

$$\eta_1 = \frac{P_1}{P_T} \quad (21)$$

$$\eta_2 = \frac{P_2}{P_T} \quad (22)$$

$$\eta_3 = \frac{P_3}{P_T} \quad (23)$$

where η_1 , η_2 , and η_3 are the modal coupling efficiencies. It is desirable to make η_1 as close to unity as possible and η_2 and η_3 as close to zero as possible. The loss of transmitter power to Mode 2 and Mode 3, in decibels, is

$$\alpha_1 = -10\log\eta_1 \quad (24)$$

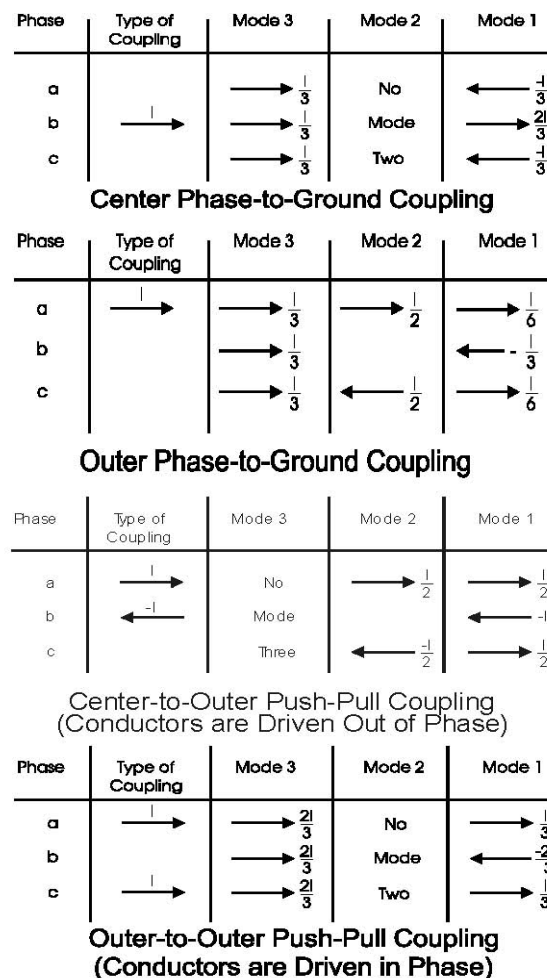
This loss may or may not be a real loss to the receiver, depending on the line length. Table 8 lists values of α_1 , as conversion losses for several common coupling methods. The table is based on the assumption that the line is sufficiently long that the received power in Mode 2 and Mode 3 is negligible compared with the power in Mode 1. Refer to 5.2 for practical guidelines.

The modal coupling efficiency is often expressed in decibels and means the same as the modal conversion loss, except that the sign is reversed. For example, center-phase-to-ground coupling, which has a modal conversion loss of 1.8 dB, is said to have a coupling efficiency of -1.8 dB.

Table 8—Mode 1 single-end conversion losses

Type of coupling	Conversion loss (dB)
Mode 1	0.0
Center phase to outer phase (conductors driven electrically out of phase)	1.2
Center phase to ground	1.8
Outer phase to ground	7.0
Double phase to ground (two outer conductors driven electrically in phase)	4.8

A representation of how the method of coupling affects the solution of modal analysis is illustrated in Figure 15.

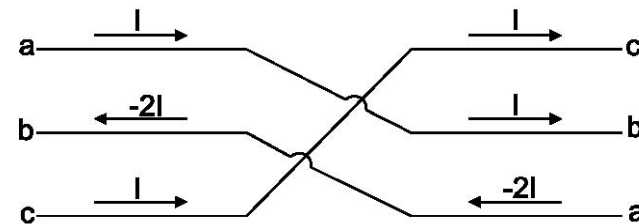
**Figure 15—Modal distribution for different coupling methods**

5.3.3.1.3 Transpositions in the line

On a long transmission line of flat construction, the 60 Hz impedance between phases is unbalanced. To aid in the removal of unbalanced currents, transpositions are placed at strategic points along the line. These transpositions affect not only power frequencies but also carrier frequencies. At carrier frequencies, transpositions are assumed to be transparent; that is, they do not reflect any incident RF energy. They do, however, act as mode converters. The value of the modal quantities at the input of the transposition will be different from the modal quantities at the output. As an example, even if only Mode 1 signals are present at the input of the transposition, all three modes of propagation are present at the output. Most output energy will be in Mode 1 and Mode 2. However, the Mode 1 quantity at the output is 6 dB below its input value. If the generated Mode 2 signal is completely attenuated before reaching the receiver or the next transposition, then 6 dB is the loss represented by the transposition. The figure of 6 dB loss is a maximum, and this simple example does not usually hold in practice, because quantities other than Mode 1 are usually present at the input to the transposition, and the generated Mode 2 is not completely attenuated by the time the receiver is reached. The exact procedure for handling transpositions in attenuation calculations is as follows:

- Calculate the modal quantities at the input to the transposition, both phase and magnitude.
- Add the modal quantities vectorally to get phase quantities.
- Transpose the phase quantities per line transposition.
- Reconvert phase quantities into modal quantities, and continue to the receiving end or next transposition. The conversion to modes is the same method as that described for coupling conversion in Equation (14), Equation (15), and Equation (16).

Figure 16 illustrates the modal conversion created during a transposition.



Phase Currents	Mode 3	Mode 2	Mode 1
$\xrightarrow{1}$	0	$\xrightarrow{1\frac{1}{2}}$	$\xleftarrow{\frac{1}{2}}$
$\xrightarrow{1}$	0		$\xrightarrow{1}$
$\xleftarrow{-2}$	0	$\xleftarrow{1\frac{1}{2}}$	$\xleftarrow{\frac{1}{2}}$

$$\text{Mode 3: } \frac{1}{3} (I_a + I_b + I_c) = \frac{1}{3} (1+1-2) = 0$$

$$\text{Mode 2: } \frac{1}{2} (I_a - I_c) = \frac{1}{2} (1+2) = 1\frac{1}{2}$$

$$\text{Mode 1: } \frac{1}{6} (I_a - 2I_b + I_c) = \frac{1}{6} (1-2-2) = -\frac{3}{6} = -\frac{1}{2}$$

Note that the mode 1 current after the transposition is half of the mode 1 current into the transposition, thus the mode 1 conversion loss is 6 dB.

Figure 16—Modal conversion at transposition

5.3.3.1.4 Receiving terminal

At the receiving terminal, the modal components are converted into phase voltages and currents. These voltages and currents then become the received signals, provided the line is properly terminated. Proper termination for all modes of propagation would require a network of six impedances (see Figure 7). In most examples of actual practice, each coupled phase is terminated with an impedance to ground. As a result, some reflections will occur, but these usually do not significantly degrade the desired signals.

The conversion factors listed in Table 4 are the result of many calculations on lines of different lengths, with or without transpositions, compared with actual measured losses. There are instances, especially when coupling to outside phase wires on horizontally constructed lines, where a physical analysis will give the only correct estimate of the actual line losses across a band of frequencies. The results for most simplified analysis calculations are conservative.

5.3.4 Physical modal analysis

The most accurate modal analysis is the physical analysis, which considers all of the variables present in the line being evaluated. Modal analysis states that there are as many modes as the number of conductors or paths in the system. A typical HV line with three phase wires and two insulated overhead static wires would have five modes because of the conductors and two related to the ground conductivity. Twin circuits will cause other modes to be established. Coupling to circuits on the same right-of-way can be studied by including the parameters of this circuit in the data. The parameters of phase and ground wire conductors are available in several sources.

5.4 Noise

5.4.1 Impulse and random noise

The performance of a relaying channel, as noted earlier, depends essentially on the SNR at the receiving end. The noise on the power line limits the amount of attenuation that a PLC channel can tolerate. Figure 17 and Figure 18 give typical values of average (random) and impulse noise on power lines, respectively. The noise levels in Figure 17 are typical average noise levels in a 3 kHz bandwidth at a 50 Ω impedance level. In Figure 17 and Figure 18, it is estimated that values given for adverse weather are not exceeded more than 1% of the time and those for fair weather not more than 25% of the time.

Figure 18, on the other hand, shows impulse noise levels over the nominal carrier frequency band. See Castro et al. [B48] for more information.

5.4.2 Noise measurements

Noise measurements have been classified according to the responses of various measuring instrument detectors to different noise characteristics. These distinctions are useful because of their different effects on various kinds of carrier receivers.

The peak value of power-line noise is the maximum voltage amplitude of recurring impulses. It is these impulses, for example, that effect trigger circuits such as are found in electronic switching devices.

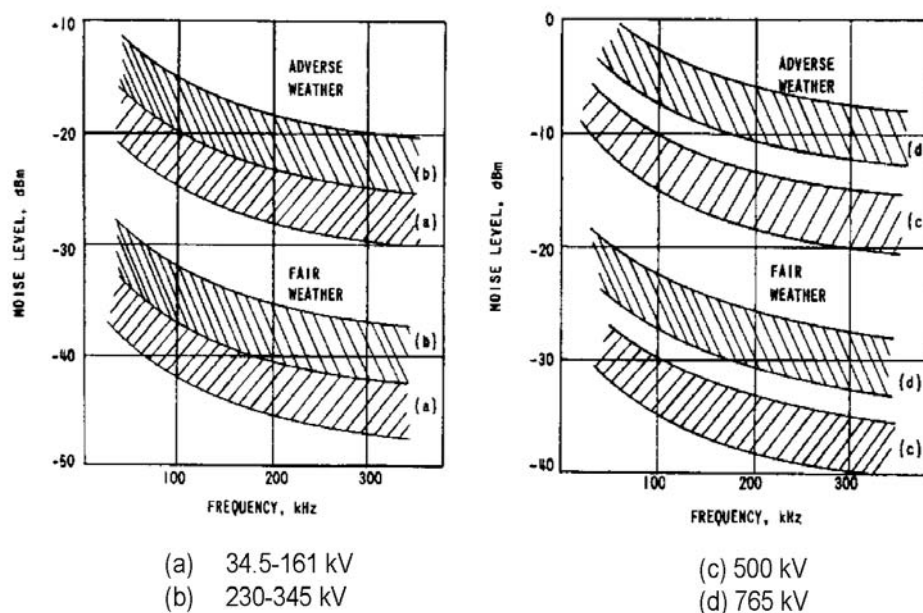


Figure 17—Range of transmission line noise levels (3 kHz bandwidth)

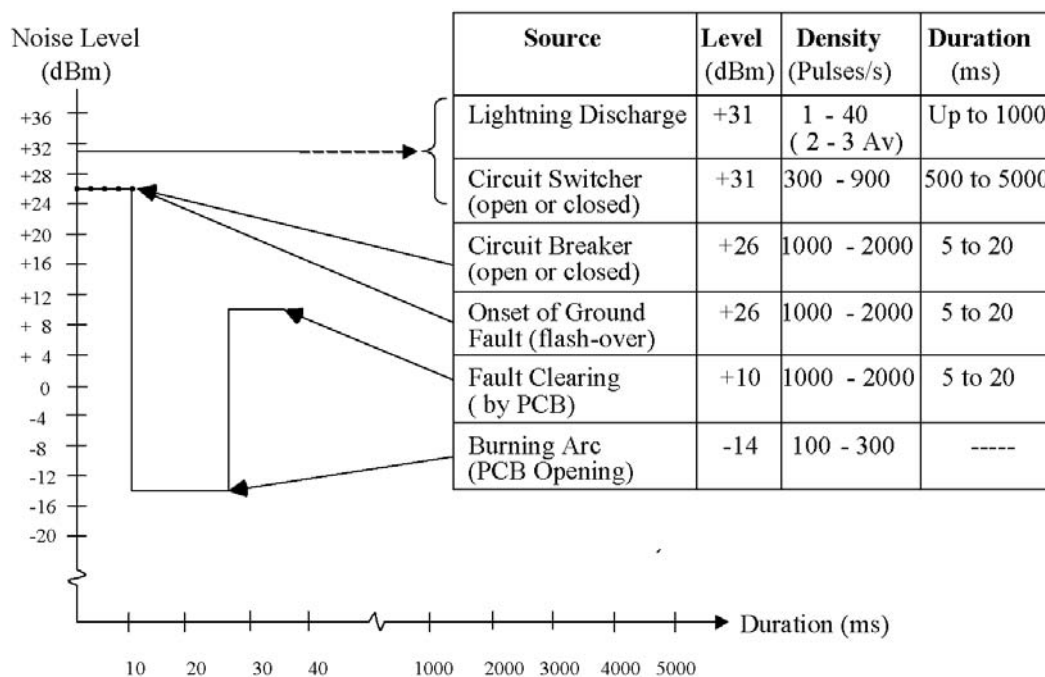


Figure 18—Typical average impulse noise levels on power lines (4 kHz bandwidth)

The quasi-peak value of noise is a reference level related to peak amplitude and to impulse repetition rate. It is measured by a detector circuit with a fast charging time and a relatively slow discharge time (typically 1 ms and 600 ms, respectively; see ANSI C63.2). For pulses occurring at high repetition rates, the quasi-peak value approaches the peak value. Quasi-peak noise is a measure of the masking effect of noise as a background for speech. The average value of noise is its average voltage over a finite period of time. It is defined as the area under the amplitude-time curve divided by the base length (time period). Average noise affects receiver-detector dc output for telegraph functions, for continuous wave relaying, or for ON-OFF pulse functions.

The RMS value of noise is the effective voltage of a reference sine wave that would have the same average power level as the noise being measured. RMS noise is of secondary importance in carrier equipment.

Peak values of noise may be measured by certain peak-reading voltmeters. So-called memory voltmeters can retain the peak reading of the highest amplitude impulse (lasting 1 μ s or longer) occurring during any arbitrary measuring period. Peak values of noise may also be measured by using a cathode ray oscilloscope; however, this usually takes a fairly elaborate setup, including photographic equipment. Quasi-peak values may be measured only by noise meters that have appropriate detector characteristics. Although used extensively for measurements of noise affecting radio broadcast, quasi-peak measurements have not been used to any great extent in carrier applications. Average values of noise may be measured by selective carrier-frequency voltmeters of known bandwidth. Also, average noise can be derived from audio noise measurements made at the output of a single-sideband carrier receiver. Because noise energy is distributed throughout the frequency spectrum, measured values will be a function of the bandwidth of the measuring instrument. As might be expected, changing the bandwidth influences peak and quasi-peak readings more than average and RMS readings. Measured peak and quasi-peak values would be lowered by approximately 6 dB if the bandwidth was reduced by 2:1. The measured values of average and RMS noise would be lowered by 3 dB under the same conditions.

Measured power-line noise often displays erratic frequency characteristics or severe standing wave patterns. The noise level on a power line is determined by both generation and propagation of noise energy. Propagation phenomena, such as attenuation, reflections, and absorptions, affect noise voltages in the same way they affect desired carrier signals.

The amplitude of power-line noise decreases with increasing frequency. A rule of thumb (very popular in the past) is that the noise amplitude varies inversely as the frequency. This would mean that the noise level drops 6 dB each time the frequency is doubled. Recent investigations have clarified that the amplitude-frequency curve is not as steep as this rule would indicate.

5.4.3 HVDC converter noise

The construction of ac to dc to ac converters and the building of HVDC transmission lines has presented new noise concerns for utilities whose ac lines are connected to these systems, and to those lines crossing or in parallel with dc lines. The noise caused by the valves in the conversion process from dc to ac is frequency dependent. The noise levels are very high at the low end of the PLC frequency band and follow an approximate 1/f characteristic to 100 kHz. The noise conducted from the converter onto the ac system requires noise filtering in the PLC frequency range to reduce this noise to acceptable levels.

High currents may exist in the frequency band from a few kilohertz to 30 kHz, which are not usually treated by the filtering at the converter. These currents can be coupled into PLC circuits. The drain coils in the coupling capacitors are designed to shunt power frequency current to ground and are designed for a maximum current. The addition of other frequency components that cause resonance, between the coupling capacitor and the drain coil, can cause saturation of drain coils using magnetic cores. The saturation of the cores results in the generation of harmonics of frequencies present in the drain coil. Many of these harmonics are in the PLC band and can generate interference for PLC channels used on the line. Drain coils with no magnetic cores do not saturate, and no frequencies in the PLC band are generated.