

An American National Standard

IEEE Guide for Power-Line Carrier Applications

Sponsor
**Power System Communications Committee
of the
IEEE Power Engineering Society**

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IEEE Standards Board

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Foreword

(This Foreword is not a part of IEEE Std 643-1980, IEEE Guide for Power-Line Carrier Applications.)

In June 1954 the AIEE Committee Report, Guide to Application and Treatment of Channels for Power-Line Carrier, was published in the *AIEE Transactions*. A revision of the guide has not been prepared since that time. Substantial changes in available equipment and practices have occurred, and preparation of an up-to-date-guide is long overdue. Hopefully this guide will meet that need.

The use of power line carrier (PLC) for the purposes of voice communication, protective relaying, supervisory operations, etc, is not unique to North America. While it has not been possible to describe where some differences may occur in application techniques and philosophies, the basic principles remain the same in all parts of the world. These differences, plus the related national and international standards, sometimes give rise to variations in equipment as compared to North American practice. Coordination with the related standards is achieved by maintaining contact with the appropriate organizations, such as IEC/TC33, 38, and 57; CIGRE 34, 35, and 36; CCITT; CCIR; CISPR; and ITU.

Both IEC and CIGRE are published PLC guides emphasizing international practices.

This guide was prepared by the Carrier Subcommittee of the Power System Communications Committee of the IEEE Power Engineering Society. At the time this guide was approved the members of the subcommittee were:

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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. Information related to the expanding usage of carriers on distribution lines is not specifically covered. Detailed equipment design information is avoided as this is primarily the concern of equipment manufacturers.

The Carrier Subcommittee has endeavored to provide curves and tables to present performance data. Complex formulas have been avoided to free the user from extensive calculations. The text provides British units of measurement followed by approximate metric equivalents in parentheses.

It is hoped that this guide will be useful to the initial user of power line carriers as well as to the experienced application engineer. Detailed references have been provided in the guide for those who require more information.

Material on power line carrier channel characteristics is presented in Section 3 along with discussions on intrabundle conductor systems and insulated shield wire systems. Section 4 provides procedures for the calculation of channel performance. Data for the calculations are drawn from various sections of the guide. Coupling components are discussed in Section 5. Major coupling components considered are line traps, coupling capacitors, line tuners, coaxial cables, hybrids, and filters. Frequency selection practices are discussed in Section 6, future trends in Section 7, and a bibliography is listed in Section 8.

This guide supersedes the now outdated AIEE Committee Report, Guide to the Application and Treatment of Channels for Power-Line Carrier [1].¹ There is unavoidable overlap in coverage between this IEEE guide and the PLC guides published by the IEC [2] and CIGRE [3]. However, all three scopes are sufficiently different that each has its own unique value.

¹The numbers in brackets correspond to the references listed in Section 2 of this guide.

2. References

2.1 Periodicals and Books

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- [2] IEC *COMMITTEE REPORT*. Manual for the Planning of (SSB) Powerline Carrier Systems, in preparation, 1979.
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[18] WOOD, T. D, JR. Application and Operating Experience of Carrier Communications over Insulated Static Wire, presented at the 1966 IEEE Winter Power Meeting, New York, NY, Jan 30-Feb 4, Paper 31-CP-66-41.

[19] ALSLEBEN, E., FINCKH, B., and LAUTENSACH, H. Telecommunication by Means of Aerial Cables on Power Lines, CIGRE Paper 35-05, presented at Paris, France, Aug 28-Sept 6, 1972.

2.2 Standards Publications

[20] ANSI/IEEE C37.90-1978, Relays and Relay Systems Associated with Electric Power Apparatus

[21] ANSI C63.2-1979, Specifications for Electromagnetic Noise and Field-Strength Instrumentation, 10 kHz to 1 GHz

[22] ANSI C93.1-1972, Requirements for Power Line Coupling Capacitors

[23] ANSI C93.2-1978, Requirements for Power Line Coupling Capacitor Voltage Transformers

[24] ANSI C93.3-1978, Requirements for Line Traps

[25] ANSI/IEEE Std 430-1976, Procedures for Measurement of Radio Noise from Overhead Power Lines

2.3 Applicable Document in Preparation²

3. Power-Line-Carrier Channels

3.1 Channel Description

A power-line-carrier (PLC) channel includes the signal path from the transmitting electronic equipment at one terminal, through its tuning 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.

In planning a channel, consideration must be given to confining carrier signals to a desired path and to excluding unwanted signals from it. These functions can be achieved to a very practical extent through the use of line traps, coupling capacitors, and line tuners to provide high-impedance blocks in the undesired paths and low-impedance paths in the desired directions.

A typical PLC channel, utilizing center phase-to-ground coupling, is shown in Fig 1. Note that this is a bidirectional application with both directions of transmission sharing a common path. A transmitter signal from one end (station A) passes through a line tuner which, in conjunction with the coupling capacitor, provides a low-impedance path between the transmitter and the line. The tuner contains an impedance matching transformer, so that the electronic equipment and the line each interface with the proper impedance. The line trap provides a high impedance at the channel frequencies to minimize loss of carrier signal power into the low impedance of the station bus. Similarly the other line trap at station B largely confines the signal power in its intended path to the electronic equipment at that end.

²When the following document is completed, approved and published, it will become a part of this listing.
Requirements for Line Traps, ANSI 93.3

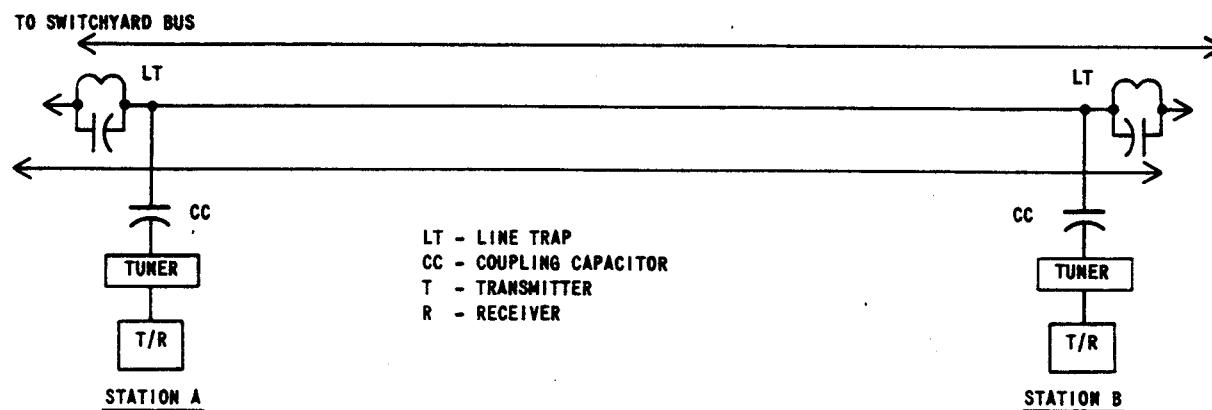


Figure 1—Diagram of a PLC Channel

The electronic equipment at the terminal ends varies significantly, depending on the purpose for which the channel is intended. PLC channels are applied as line relaying or transferred trip channels. They are also used as single-sideband voice, data, supervisory, and control channels. Single-sideband voice channels and other functions are sometimes applied as combined channels.

Included in the definition of PLC channels are other arrangements in which power cables, power cables in series with overhead power lines, or insulated ground wires are utilized as transmission paths. Various coupling methods are used for these combinations.

Insulated shield wires are not normally recommended for protective relaying applications.

3.2 Characteristic Impedance

The *characteristic impedance* [4], [5] 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 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 = resistance per unit length, in ohms
- L = inductance per unit length, in henrys
- G = shunt conductance per unit length, in mhos (siemens)
- C = shunt capacitance per unit length, in farads
- ω = $2\pi f$, f being frequency in Hz

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 Eq 2,

$$Z_0 = 276 \log \frac{D}{r} \times \frac{D}{r} \geq 20 \quad (3)$$

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

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

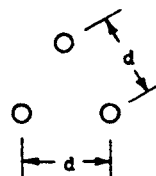
TWO-WIRE BUNDLES

$$GMR = \sqrt{GMR_c \cdot d}$$



THREE-WIRE BUNDLES

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



FOUR-WIRE BUNDLES

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

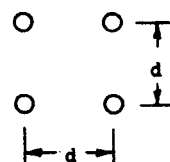


Figure 2—Geometric-Mean Radius of Conductor Bundles, GMR_c

For bunched conductors the *geometric mean radius* (GMR) is used for r in Eqs 3 and 4. The GMR is defined in Fig 2 for three arrangements.

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 bunched 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 were infinitely long.

An impedance network of six impedances, as shown in Fig 3, is required to terminate a three-phase line in its characteristic impedance. Since a transmission line is seldom, if ever, terminated in its characteristic impedance network, the impedance seen by a set of coupling equipment connected to the transmission line, either phase to phase or phase to ground, will be reflected energy on the uncoupled phases affected by reflected energy on the uncoupled phases.

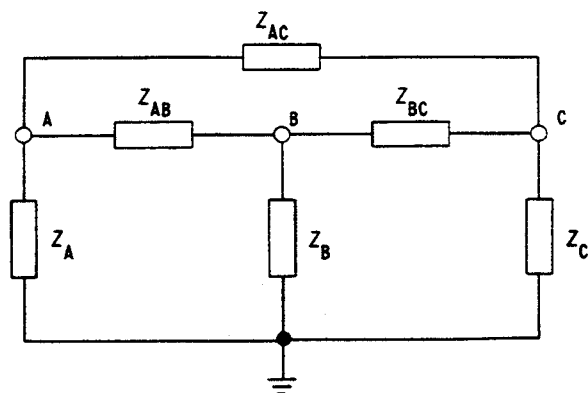


Figure 3—Terminating Network for a Three-Phase Line

Another and more practical value frequently called characteristic impedance is the value of the impedance to which the carrier coupling equipment is matched in order 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, the (practical) characteristic impedance is not very dependent on the terminating impedance of the uncoupled phase. However, much larger differences occur for phase-to-ground coupling, as the terminating impedance of the uncoupled phases varies from an open circuit to a short circuit.

As shown in Eq 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 Phase to Ground (ohms)	Phase to Phase (ohms)
Single wire	350–500	650–800
Bundled (2-wire)	250–400	500–600
Bundled (4-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 .

3.3 Power-Line Noise

3.3.1 Noise Types

Noise voltage within the carrier frequency spectrum, which exists on every power line, must be considered in the design of PLC circuits to ensure that the required degree of reliability is provided. Different types of noise have different influences on various carrier facilities. This section describes the essential characteristics of noise and identifies those types that have the most serious effects on the *reliability*³ of carrier circuits (see ANSI/IEEE C37.90.1978, [20]).

Power-line noise has generally been placed in two categories, called *random* noise and *impulse* noise. Random noise has a continuous frequency spectrum and has been compared to white noise, while impulse noise consists of sharp, separate impulses, produced by specific electrical discharges. Power-line noise is predominantly of the impulse type in which the pulse peaks are well above the average level and the space between pulses is occupied by random noise. For PLC applications, in lieu of the distinction between random noise and impulse noise, it is frequently useful to distinguish between noise that occurs as a continuous function of time and noise that occur as short, duration noise bursts which are nonperiodic.

3.3.2 Causes and Effects of Noise

Random noise can be caused by thermal agitation in the power-line conductors, certain atmospheric and static discharges, and low-level corona discharges. Small discharges at many different points, although individually impulsive, together add up to random noise.

Because of their high repetition frequency, many sources of periodically recurring impulses create noise that is essentially continuous as a function of both time and frequency. Sources of this type of noise include rotating machinery, power rectifiers, arc furnaces, and high-level corona discharges which are frequently produced during heavy rain.

Lightning, line faults, circuit breaker operation, arcing of disconnect switches, and many lesser transients produced within a power station are examples of short-duration noise bursts and sharp, well-separated noise impulses which do not recur at periodic intervals.

Intelligibility in telephone circuits, error rate in data circuits, dependability in protective relaying circuits, reproduction quality in facsimile circuits, and many other similar characteristics of PLC services depend largely on the signal-to-noise ratio determined by noise, which is present as a continuous function of time. Since these services are expected to operate continuously, design parameters for a required minimum signal-to-noise ratio will be determined by the highest level that this noise may be expected to attain.

Bad weather increases the line noise level. Thunderstorms produce discharges which result in line noise as great as 10 times (20 dB higher than) the fair-weather figure. Corona generated on the surface of transmission line conductors during wet weather is sometimes the predominant source of worst case noise, especially on EHV lines. Severe corona noise may be as much as 30 dB above fair-weather levels.

Corona is a luminous discharge due to ionization of the air surrounding a conductor when the voltage gradient at any point on its surface exceeds a critical value. Current impulses (or short trains of impulses) resulting from these discharges may be generated during each positive half-cycle of the power-frequency voltage, resulting in a basic burst repetition frequency of 180 Hz for a 60 Hz, three-phase system. Corona noise has an amplitude characteristic that decreases with increasing frequency. Its energy is continuous throughout the spectrum from frequencies below the

³The definition of *reliability* as applied to relays and relay systems can also be of benefit in studies of PLC circuits. Reliability is the degree of certainty that a circuit (or system) will perform correctly whenever required and resist misoperation at all times. These two aspects of reliability are defined separately as *dependability* and *security*. Dependability in a system is the ability to operate properly when called upon to do so in the presence of any noise which exists at the time. Security is the ability to resist false response due to interference from any source which occurs while the system is in service.

PLC band to beyond the high-frequency (HF) radio band. Corona noise generally becomes insignificant at frequencies in the mid-VHF region, except during ice and snow conditions. The mechanism for corona generation and the factors that influence it have been described in numerous publications [6].

Various transmission-line parameters affect line noise mainly because they affect corona. Constant and variable factors, such as voltage class, voltage fluctuations, line geometry (including conductor size and bundling arrangements), conductor surface condition, and weather, all affect conductor corona generation and, hence, noise.

In comparison to corona noise on conductors, noise produced by corona on insulators, hardware, and station apparatus is usually of secondary concern at PLC frequencies. Similarly, gap-type noise generated in faulty hardware, cracked insulators, or improperly bonded high-voltage apparatus often causes VHF problems such as television interference when it occurs, but produces insignificant disturbance in the PLC band.

Nonrecurrent high-level noise bursts are usually not of great concern in the dependability of most carrier circuits. For example, a loud noise burst in a telephone circuit, while bothersome, does not impair the intelligibility of the circuit following the burst. Similarly, isolated hits causing a number of momentary errors in a data circuit do not seriously impair its error rate on a day-in, day-out basis. The most detrimental effects which a high-level noise burst might produce are possible damage to circuit components and loss of security in circuit functions such as direct transferred-trip protective relaying.

The noise characteristics on a transmission line during a fault are rather complex [7]. When a fault occurs, there is an initial burst of HF noise which usually decays within 1.5–4 ms. The actual peak value, lasting about 2 μ s, may be well over 1000 V in amplitude. This is followed by a period of much lower noise level until the circuit breaker interrupts the fault current, at which time another short burst of HF noise occurs. A diminishing low-level noise exists during deionization of the fault arc which lasts for about 16 ms.

Although lightning during adverse weather is sometimes troublesome, the source of noise that has the most detrimental influence on the security of protective relay circuits is the arc that occurs during the operation of a disconnect switch. This arc creates a burst of noise impulses that will last for at least a second. During most of the arcing time the impulse repetition frequency is 720 Hz for a 60 Hz, three-phase system. The frequency spectrum of this noise burst does not have a decreasing amplitude characteristic like that of corona and random noise. Instead it increases gradually in amplitude up to some frequency which is dependent on the electrical length of the switchyard buses and other apparatus connected to the arcing switch. Typically, maximum amplitude occurs at a frequency near 1 MHz. This high-intensity noise contains impulses frequently exceeding 1000V peak across a terminated coaxial cable.

3.3.3 Measuring Noise

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 affect trigger circuits such as are found in electronic switching devices.

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 C63.2-1979, [21]). 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 telegraphic 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 which 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, including standard noise meters. So-called memory voltmeters can retain the peak reading of the highest amplitude impulse (lasting 1 μ s or longer) which occurs 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 broadcast radio, 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.

Since 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 were reduced 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 as 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 that the frequency is doubled. Recent investigations have clarified that the slope of the amplitude-frequency curve is not as steep as this rule would indicate. The curves of Fig 4 portray average noise in a 3 kHz bandwidth for a number of different line voltage classifications and also for both fair and adverse weather conditions. For the user who has no direct measurements of his own circuits, these values may be applied for design purposes.

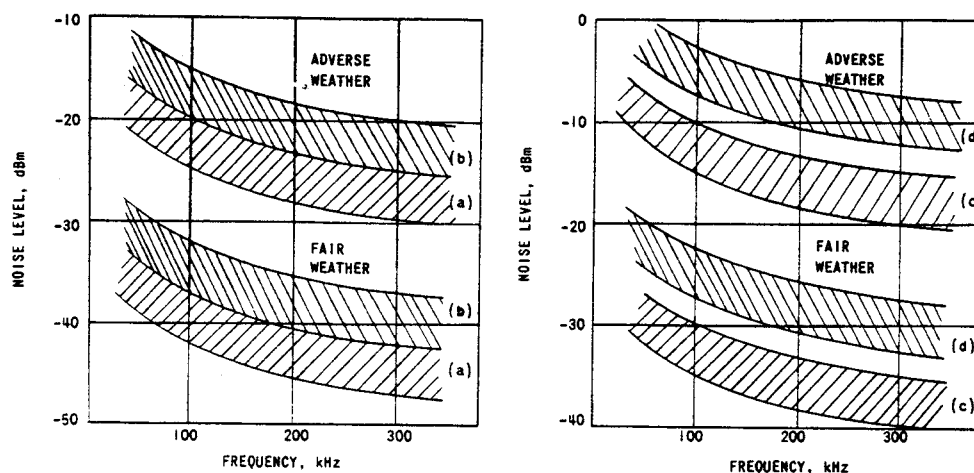


Figure 4—Transmission-Line Noise Levels in a 3 kHz Bandwidth for Different Line Voltage Ranges.
 (a) 34.5-161 kV; (b) 230-345 kV; (c) 500 kV; (d) 765 kV. It is Estimated that the Values Given for Adverse Weather are not Exceeded more than 1% of the Time and Those for Fair Weather not more than 25% of the Time.

3.3.4 Determination of PLC Noise by the RIV/RI Ratio [8]

A useful relationship in both carrier work and radio noise theory is the ratio of *radio influence voltage* (RIV) to radio interference (IRI). RIV is the term generally applied to the radio frequency (RF) line noise potential which exists on the transmission-line conductor. RIV is usually expressed in microvolts (μV) or in decibels (dB) above 1 μV . RI refers to the electromagnetic noise field at ground level in the vicinity of the transmission line. RI is usually expressed in microvolts per meter ($\mu\text{V}/\text{m}$) or in dB above 1 $\mu\text{V}/\text{m}$.

The value of this relationship to applied PLC is that if the RIV/RI ratio is known, an unknown power-line noise level can be determined without interrupting in-service carrier facilities by measuring the RI along the line and applying an appropriate conversion factor. Many utilities have established radio noise measuring programs for EHV lines from which RI data at 1 MHz are readily available.

The proper method of measuring RI has been adequately described (see ANSI/IEEE Std 430-1976, [25]). The usual procedure is to take enough readings to establish a lateral profile of RI as a function of the horizontal distance from a point directly under the center of the transmission line to a point some 200 ft (60 m) or more from the outer phase conductor.

RI measurements must be made using an appropriate instrument. Noise meters meeting the requirements of ANSI C63.2-1979 for the frequencies under consideration have an average bandwidth of about 5 kHz. The actual bandwidth of each individual noise meter and any dependence of the instrument's bandwidth on frequency will be covered in its instruction manual. These meters are capable of measuring peak, quasi-peak, and average values of noise. The average value, commonly called field intensity (FI), is the reading used for deriving RIV in the carrier band.

Table 2 lists conversion factors (for a typical single-circuit power line) by which RIV on a 50 Ω impedance base and at a frequency of 150 kHz can be obtained in μV (or in dB above 1 μV) from RI measurements made at either 150 kHz or 1 MHz. For this purpose the preferred RI measuring location is 100 ft (30 m) horizontally from the outer phase of the line. Should the surrounding terrain prevent measurements at 100 ft (30 m) conversion factors for 0 ft and 50 ft (15 m) also appear in the table. However, unless absolutely necessary, measurements at zero reference (directly under the outer phase conductor) are not recommended. In broadcast band radio noise work, for RI comparison purposes, a reference horizontal distance of 50 ft (15 m) from the outer phase of the line is considered standard.

Table 2—RI to RIV Conversion Factors

RI Measuring Frequency	Lateral Distance from Outer Conductor		Voltage Multiplier	Correction Factor (dB)
	(ft)	(m)		
1.0 MHz	100	30	240	47.5
1.0 MHz	50	15	83	38.5
1.0 MHz	0	0	45	33.0
150 kHz	100	30	60	35.5
150 kHz	50	15	21	26.5
150 kHz	0	0	11	21.0

If the RI data are in $\mu\text{V}/\text{m}$ the voltage multiplier from Table 2 is used to provide RIV in μV . If the RI data are measurements taken in dB above 1 $\mu\text{V}/\text{m}$, the dB correction factor is added to provide RIV in dB above 1 μV . Table 3 lists the equivalent noise level in dBm for a number of values of RIV in μV . Values between those listed may be interpolated on a logarithmic voltage scale or computed directly. If the RIV level is in dB above 1 μV , it is only necessary to algebraically add -107 dB to that level to obtain dBm.

Table 3—Conversion from μV across $50\ \Omega$ to dBm

μV	dBm
100	−67.0
300	−57.5
500	−53.0
1000	−47.0
2000	−41.0
4000	−35.0
6000	−31.5
8000	−29.0
10 000	−27.0
20 000	−21.0
40 000	−15.0
60 000	−11.5
80 000	− 9.0
100 000	− 7.0

In either case the noise level in dBm is the one that would have been measured within the same bandwidth as that of the radio noise meter used to make the initial RI measurements. The equivalent noise level in any other bandwidth is readily obtainable by applying a correction factor (in dB) equal to 10 times the common logarithm of the bandwidth ratio. For example, if the noise meter bandwidth were 5 kHz and power-line noise within a 3 kHz bandwidth is desired, the correction factor would be approximately 2 dB.

As an application example, assume that an RI measurement of $40\ \mu\text{V}/\text{m}$ at 1 MHz is made at a distance of 100 ft (30 m) from the outer conductor. From Table 2 the multiplier is 240. Therefore the RIV across a $50\ \Omega$ carrier termination at 150 kHz is

$$\text{RIV} = 240 \times 40 = 9600\ \mu\text{V}$$

From Table 3 (by interpolation) this corresponds to a level of approximately −27.5 dBm.

If the RI data has been in dB above $1\ \mu\text{V}/\text{m}$ ($20 \log 40 = 32$), the decibel correction factor of 47.5 dB from the table would be added:

$$\text{RIV} = 32 + 47.5 = 79.5\ \text{dB above } 1\ \mu\text{V}$$

This voltage level across $50\ \Omega$ converts to dBm as follows:

$$\text{RIV} = 79.5 - 107 = -27.5\ \text{dBm}$$

If the noise level in a 3 kHz bandwidth is desired, but the noise meter bandwidth is 5 kHz, then the 2 dB correction previously mentioned should be deducted:

$$\text{RIV} = (-27.5) - (2) = -29.5\ \text{dBm}$$

3.4 Channel Bandwidth and Modulation

3.4.1 General Bandwidth Requirements

While a frequency band from 200 to 6100 Hz permits transmission of speech without loss of fidelity, this range is seldom employed in practical voice communications systems. With a signal-to-average-noise ratio of 30 dB, word intelligibility (the percentage of a group of nonrelated words that can be recognized and understood after transmission over a communication channel) of greater than 95% can be obtained when a frequency band from 300 to 2200 Hz is used. This bandwidth affords even greater intelligibility when related words, such as those found in normal sentence structures, are used. If greater fidelity is required, such as the requirements of a commercial telephone channel, an expanded bandwidth of 300–3400 Hz can be used. Expansion beyond this bandwidth is normally reserved for high-speed data channels and is not normally found in PLC voice communication systems.

While it is obvious that different functions require different bandwidths, the use of non-standard bandwidths on various PLC equipment tends to waste frequencies allocated to PLC because of the guard bands of different widths required to prevent crosstalk between channels. In recent years the PLC industry has tended to standardize the single-sideband (SSB) channel bandwidth to 4 kHz and vary the utilization of this band to fit whatever purpose is required by the user. Thus after subtraction of approximately 300 Hz from each end, a 3400 Hz band is available for data, voice, voice pins, tone relaying, and so on. The guard bands are standard and minimize the amount of spectrum not being used for active communication. Further, there is some tendency toward allocating all services into frequency slots that are multiples of 4 kHz to provide for more orderly growth and easier, frequency planning.

Bandwidth requirements for other types of PLC channels, such as telemetry, blocking relaying, transferred trip, supervisory control, and low-speed data transmission, are varied, but generally require less bandwidth than voice. Successful 30 ms transferred-trip operations can be carried out over a channel of less than 250 Hz in bandwidth; however, wider bandwidths are used when greater speeds are required. When guard bands are included, this channel occupies a 500 Hz band. Commercial carrier relaying equipment of this bandwidth is commonly available. Frequency-shift carriers used with supervisory control, teletype, etc, may have even lower bandwidth requirements.

3.4.2 Modulation Types

Amplitude modulation (AM) is obtained by varying the amplitude of a constant-frequency carrier in proportion to the amplitude of a modulating waveform, such as a voice or tone signal. The resultant modulated signal contains the original carrier frequency plus frequencies above and below the carrier, called sidebands. The frequencies in these sidebands differ from the carrier frequency by the frequencies in the modulating waveform. These sidebands (upper and lower) each occupy the same bandwidth as the modulating signal and contain the same intelligence. For 100% modulation the power in each sideband is equivalent to one fourth the power contained in the carrier. The total bandwidth required for AM transmission is twice the highest frequency of the modulating wave.

Because of its bandwidth requirements and susceptibility to noise interference, AM is not used extensively today in PLC voice channels. The broader the receiver passband, the more energy it will pass, and the greater the effect of noise, except for coherent detection systems which have the same signal-to-noise ratio as SSB systems. AM is still used by some utilities for service voice channels. Keyed carrier (on-off AM) is commonly used for line relaying.

Single-sideband modulation (SSB) is AM with one sideband removed. In addition the carrier is usually suppressed at the transmitter and reinserted at the receiver to further reduce unnecessary power transmission, since one sideband contains all the intelligence in the modulating signal. This allows the entire power output of the transmitter to be concentrated in one intelligence-bearing sideband. The SSB bandwidth requirement is one half that required for AM. Hence it has the advantage of providing more efficient spectrum utilization. Additional advantages of SSB over conventional AM channels are a higher signal-to-noise ratio and a reduced susceptibility to corona modulation.⁴

⁴Severe corona is believed to cause channel attenuation to vary in cadence with individual cycles of the power frequency transmission-line voltage. This causes the amplitude of the received carrier signal to vary at a power frequency rate, hence the term corona modulation.

Frequency modulation (FM) results from varying the frequency of a constant-amplitude carrier in proportion to the amplitude of a modulating waveform and at its rate. An FM wave can contain many sidebands, with equal numbers above and below the carrier. Its maximum amount of frequency shift is known as frequency deviation. The single-tone modulation index is the ratio of frequency deviation to tone frequency.

The bandwidth required for FM transmission is dependent on the modulation index. With a modulation index greater than unity, the bandwidth is equal to twice the frequency deviation. As the modulation index decreases below unity, the bandwidth approximates twice the modulating frequency.

Like AM, FM is not in extensive use today for voice transmission because of large bandwidth requirements. FM does provide a relatively good signal-to-noise ratio, which increases as the modulation index increases. It finds use in noisy environments.

Frequency-shift keying (FSK) is a method by which a continuous carrier is transmitted, with the capability of being shifted to another frequency in order to initiate some function. Two-frequency and three-frequency equipments are available commercially. In two-frequency operation (sometimes called *binary FSK*) the transmitted carrier can be shifted in frequency to initiate a single function. In three-frequency operation the transmitted carrier is the center frequency and can be shifted to a lower frequency to initiate one function and to a higher frequency to initiate a second function. In other applications the FSK carrier can be continuously keyed in a manner to represent either analog or digital quantities.

FSK is particularly adaptable to protective relaying, teletype, telemetering, supervisory control, and data communication channels. Since a carrier is always present in a properly operating channel, a loss of carrier condition can initiate a channel alarm. This results in an improvement over an on-off AM channel.

3.5 Channel Losses

3.5.1 Losses

Loss is the reduction in power between two points on a communication channel. It is convenient in practice to express such losses in terms of dB, so that losses in various portions of a channel can be added to obtain the total loss. Loss in dB is defined as follows:

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

$$\text{loss} = 20 \log \frac{V_1}{V_2} \quad (5B)$$

$$\text{loss} = 20 \log \frac{I_1}{I_2} \quad (5C)$$

where P is power, V is voltage, and I is current, and the subscripts designate points of measurement in the channel. The latter two equations are valid only if the circuit impedances are equal at the points where the two currents (or voltages) are measured.

The total attenuation of a PLC communication channel consists of the line attenuation (due to resistance, radiation, induction, etc), shunt attenuation (power flowing into paths other than the desired channel), bypass losses, and coupling losses. Mismatch losses will also be present where the terminal and coupling equipment impedances are not perfectly matched to the line.

3.5.2 Attenuation in Overhead Lines

At carrier frequencies a typical power line operates as a transmission line that is long compared to a wavelength of the carrier frequency. The performance of such a transmission line can be predicted reasonably well by applying modal theory (see 3.6), provided that all the necessary line parameters are known and a suitable computer program is available to the application engineer. For most application problems, however, adequate performance predictions can be made based on attenuation measurements made on typical lines.

Line losses are primarily a function of the following parameters:

- Carrier 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

Line losses increase with increasing carrier frequency due to increasing radiation loss, conductor loss, dielectric losses, and coupling to the ground wires, the ground, and the tower structure. These losses can be reduced by using smaller phase-wire spacing-to-height ratios and higher conductivity materials in the phase wires. The line voltage imposes limitations on phase-wire spacing and height, effective phase conductor cross section, and the number and separation of conductors per phase. HV lines exhibit a decreasing loss with increasing voltage.

For economic reasons, conductors of more than one material are frequently used on power lines. A typical configuration is a core of steel wires with an outer covering of aluminum wires. The losses in such a conductor depend on the geometry and material of the wires making up the conductor.

Since carrier currents are induced in the ground wires, ground-wire conductivity influences overall line losses. Low-loss ground wires are important near the coupling points on the line if single-phase-to-ground coupling is used, since large carrier currents must sometimes flow in them to establish the low-loss propagation mode without suffering substantial coupling loss.

The loss in a line depends on the method of coupling used. Single-phase-to-ground (usually the center phase for horizontal structures) coupling is most frequently used. In situations requiring lower losses or higher probabilities of getting a signal through line faults, interphase or three-phase coupling methods are becoming increasingly popular.

A single transposition in the middle of a long line can introduce a maximum of 6 dB loss. Usually the losses are not that great, even where several transpositions are involved or the line is short.

Weather conditions can introduce significant loss, particularly where hoar frost is formed on the lines. The ratio of line attenuation with frost to fair-weather attenuation ranges from about 4:1 at 50 kHz to 5:1 at 250 kHz. Rain can double the line attenuation, particularly if it increases the conductivity of contaminants, such as heavy fly ash deposits, on the insulator surfaces.

Poor ground conductivity can cause increased line losses. This is an important factor where single-phase-to-ground coupling is used and no ground wires (or ground wires of poor conductivity) are used at the coupling point. Poor ground conductivities occur most frequently in dry, sandy soils. A good station ground mat can substantially reduce the effects of poor ground conductivity on coupling losses, provided it extends along the line for several spans.

An estimate of the line losses can be obtained by performing the operations indicated in Fig 5, using additional data from Tables 4–6 [9].

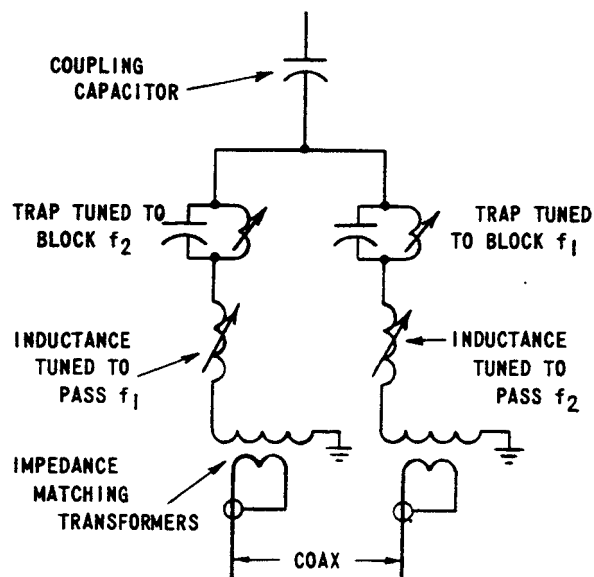


Figure 5—Method of Determining Attenuation for an Overhead Transmission Line

Table 4—Line-Voltage Multipliers

Line Voltage (kV)	Fair Weather	Adverse Weather*
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

*Under certain severe frost conditions, extreme losses can occur.

Table 5—Coupling Correction Factors

Type of Coupling/ Shield Wires	Correction (dB)		
	< 5 mi (8 km)*	> 50 mi (80 km)*	150 mi (240 km)*
Mode 1 coupling	0	−2	—
Center phase to outer phase	0	0	—
Center phase to ground:			
A1 or Cu wire	0	1	—
Steel wire	1	4	—
No shield wire [†]	8	8	—
Outer phase to ground:			
A1 or Cu wire	0	—	13
Steel wire	1	—	15
No shield wire [†]	19	—	19

*Linear interpolation should be used to determine loss between limits of line length.

[†]Subject to wide variations.

Table 6—Transposition Corrections*

Transposition	Correction (dB)	
	<10 mi (16 km) [†]	>100 mi (160 km) [†]
1	0	6
2–4	0	8
5 or more	0	10

*Apply for 345 kV and higher

[†]Linear interpolation should be used to determine loss between limits of line length.

3.5.3 Attenuation in Power Cables

Carrier propagation losses per unit length in a power cable are substantially larger than those experienced with overhead phase wires. The specific loss encountered with a particular cable depends on its construction and the method of coupling. Individual power cable manufacturers may be able to supply attenuation and characteristic impedance information.

The two power cable types generally used in underground applications are single-conductor self-contained cables and single- or three-conductor pipe-type cables [10]. It should be noted that experimental work is being done on cryogenic cables, but they are not yet being applied. Single-conductor self-contained cables utilize a hollow oil-filled conductor and an oil-impregnated paper insulation. An extruded metallic shield encases the insulation. The pipe-type cable utilizes a solid conductor with oil-impregnated paper insulation which is wrapped with synthetic tape layers and thin metallic tapes. One or three conductors are housed in a pipe which is filled with high-pressure oil (or gas). In some applications the fluid is pumped through the pipe to provide a more uniform temperature distribution and cooled to remove heat from the cable. Protective skid wires are spiraled around the conductor or conductors to protect them during insertion. The conductivity of these skid wires affects carrier attenuation. Characteristic impedances in power cables vary over a range from about 10 to 60 Ω .

Representative values of attenuation on a power cable are shown in Fig 6 for a single-phase-to-ground input. Mutual coupling between phases in a three-conductor pipe-type power cable varies with frequency. At lower frequencies, attenuation with interphase coupling is substantially lower than with phase-to-ground coupling.

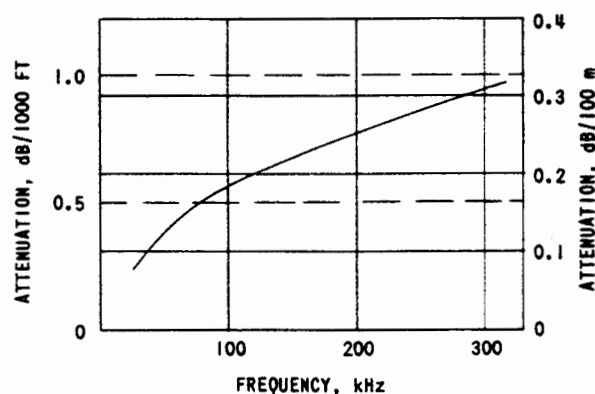


Figure 6—Phase-to-Ground Attenuation on a 138 kV Pipe-Type Cable

3.5.4 Attenuation at Discontinuities

When a relatively short line is terminated in a load that is different from its characteristic impedance, the variation in line input impedance due to reflected energy can cause a transmitter to operate inefficiently. The effects of wide variations in input impedance can be minimized by a proper selection of frequencies provided that the distance to the mismatch and the magnitude of the mismatch termination are known. Any change in the line could lead to an input impedance change, however. In some cases a mismatch can be overcome by adjustment of the line tuner and changing the impedance-transformer ratio. Where a mismatch point is isolated from the input end of a line by substantial line loss, there is little change in input impedance due to reflected energy, and the only additional loss is due to the energy reflected from the mismatch.

The loss due to an impedance discontinuity between a line of characteristic impedance Z_0 and a load impedance Z_1 is given in dB by the formula

$$\text{mismatch loss} = 20 \log \left| \frac{Z_0 + Z_1}{2Z_0Z_1} \right| \quad (6)$$

Sometimes a tap line is connected to the existing power line between two stations. If the line is short (low loss), its behavior as a stub at all carrier frequencies on the line should be investigated. If the stub is terminated in a high impedance and its length is equal to an odd number of quarter-wave-lengths at the carrier frequency, a low impedance will be reflected across the main line at the junction. For example, if the stub length is one quarter-wavelength at a given carrier frequency and the end of the stub is terminated in an open circuit, a short-circuit impedance will be reflected across the main line. This will result in an essentially infinite loss to the carrier-frequency signal on the line. Similarly, if a short stub is terminated in a low impedance at a carrier frequency and its length is an even number of quarter-wavelengths at that frequency, a low impedance will again be reflected across the junction.

If a high loss is present on a line due to a stub, the situation may be eliminated by changing the carrier frequency. However, this cannot always be done, and the most effective method for minimizing a problem with a stub is usually to install a line trap at the input to the stub line.

3.5.5 Attenuation in a Combined Overhead Line and Cable

When an overhead line connects directly to a power cable, a substantial impedance mismatch occurs. This causes signal attenuation due to energy reflection. Typically the overhead line might have a characteristic impedance of $300\ \Omega$ (phase to ground), and the power cable might have a characteristic impedance of $20\ \Omega$, resulting in an impedance mismatch ratio of 15:1. This is found to result in a 6.3 dB mismatch loss (Fig 7).

As discussed in the previous section, the input impedance to the overhead line may vary substantially from its characteristic impedance if a mismatch is present and the overhead line has low attenuation. Particularly bad situations occur where overhead line lengths are multiples of one quarter-wavelength at the carrier frequency. This can readily be seen for the case of a quarter-wavelength line segment, since it acts as an impedance transformer in which the input impedance Z_{in} is defined by the expression (for a lossless line)

$$Z_{in} = \frac{Z_0^2}{R} \quad (7)$$

where Z_0 is the characteristic impedance and R is the load. For $Z_0 = 300\ \Omega$ and $R = 20\ \Omega$, $Z_{in} = 4500\ \Omega$, which is very high compared to the $300\ \Omega$ characteristic impedance. A half-wavelength line segment is equivalent to two quarter-wavelength segments back to back, and the input impedance to the overhead line would equal the load resistance of $20\ \Omega$, which is very low compared to $300\ \Omega$. Other multiples of one quarter-wavelength result in either a high- or a low-input impedance.

Fig 7 is a graph of the mismatch loss as a function of the *in-phase* impedance ratio. Mismatch losses also occur when there is a phase angle associated with the mismatch ratio. For this reason, mismatch losses due to wide variations in the input impedance to the overhead line cannot be *directly* avoided, even by using frequencies that result in an odd number of one-eighth-wavelengths over the line length, because the lower mismatch ratio assumes a complex nature. However, for these in-between frequencies the resistive component of input impedance is usually within the range of adjustment of the impedance-matching transformer, and the reactive component can be offset by adjustment of the line tuner. Fairly efficient operation within a limited bandwidth is possible.

The deleterious effect of reflections on the input impedance to an overhead line is greatly reduced if the line loss exceeds 5 dB.

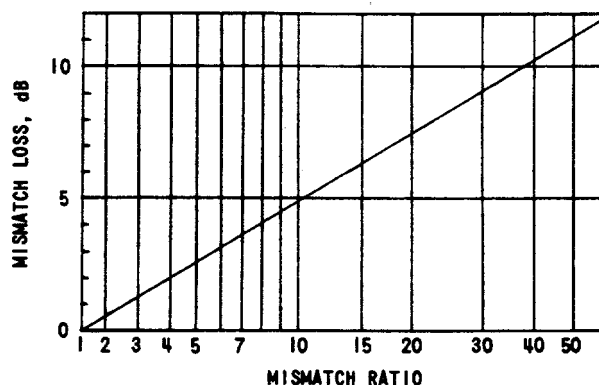


Figure 7—Mismatch Loss

The input impedance to the cable end of a combined system is also sensitive to the impedance mismatch at the junction of the cable and overhead line. Frequencies for which the power cable length corresponds to an odd multiple of an

eighth-wavelength are to be preferred over those for which the length is any multiple of a quarter-wavelength. As with the overhead line, the effect of reflections can usually be neglected for cables having more than 5 dB attenuation.

Although the effect of reflected energy on the input impedances to the overhead line and the power cable can be minimized by careful frequency selection and compromise adjustments of line-tuning equipment at both ends, the present application trend is to provide line trap isolation for the carrier circuit between the overhead line and the power cable. Coupling capacitors, line tuners, and impedance-matching transformers can then be used to provide the proper impedance to both the overhead line and the cable, and mismatch loss as well as frequency selection problems can be eliminated.

3.5.6 Coupling Losses

3.5.6.1 General

Coupling losses are the losses that occur between an individual transmitter or receiver and the power line to which it is coupled. They include hybrid and after losses associated with the coupling circuits, tuner losses, coaxial cable losses, coupling capacitor losses, and shunt losses.

3.5.6.2 Carrier-Frequency Separation Equipment

Several transmitters and receivers on a common coupling circuit require isolation elements to prevent undue signal absorption, interference, and intermodulation. These signal separation elements (typically hybrid units, trap units, series L/C units, and various filters) cause attenuation of the signal. The magnitude of loss varies widely, depending on the type, characteristics, and combination of the separation elements. Values must be obtained from the manufacturer for specific configurations and equipment. Refer to 5.5 for further discussion.

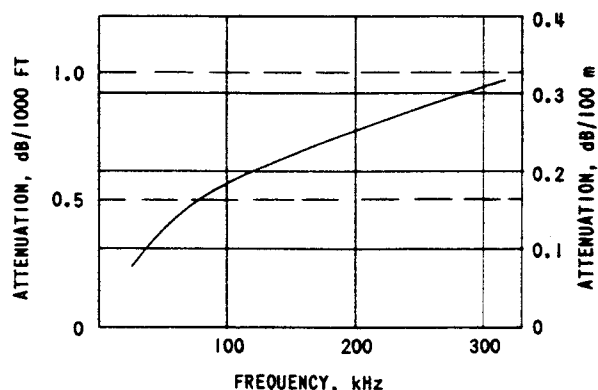
The attenuation caused by these various elements when they are connected between a carrier transmitter (or receiver) and the line tuner is given in Table 7.

3.5.6.3 Coaxial Cable

Transmitter/receiver equipment is normally connected by coaxial cable to a line tuner located near or in the base of the coupling capacitor. A representative type of coaxial cable, RG-8/U, has an attenuation that varies with frequency, as shown in Fig 8.

Table 7—Attenuation of Separation Elements

Separation Equipment	Attenuation (dB)
Hybrid	3.5
Skewed hybrid	
Transmitter arm	0.5
Receiver arm	12
L/C unit	1–3
Filter (low pass, band pass, or high pass)	1

**Figure 8—Attenuation in RG-8/U Coaxial Cable**

3.5.6.4 Line Tuner Losses

A detailed discussion of various line tuners is presented in 5.3, including curves for determining losses in various classes of tuners. For quick estimates, values to be expected with a $0.003 \mu\text{F}$ coupling capacitor, a 300Ω line impedance, and a frequency of 100 kHz are as follows:

Single-tuned resonant coupler	0.5 dB
Double-tuned resonant coupler	1.0 dB
Bandpass coupler	1.0 dB

3.5.6.5 Coupling Capacitor Losses

A high dissipation factor in a coupling capacitor can produce an effective series resistance of several ohms at carrier frequencies. This resistance will cause I^2R losses to the carrier channel. The impedance level associated with PLC on overhead transmission lines is high enough that this loss is usually only a fraction of 1 dB. It may consequently be either neglected or considered a part of the line tuner loss. On low-impedance power cables, however, series coupling capacitor loss may be several dB and represent a significant portion of the total coupling losses.

The capacitance of a normal coupling capacitor is a function of temperature. Changes in capacitance caused by changes in temperature can result in detuning of the resonance between the coupling capacitor and its associated line tuner. The selectivity associated with most coupling circuits on overhead transmission lines is usually broad enough (except at very low frequencies) that detuning caused by temperature changes can be neglected. But PLC channels on

low-impedance power cables may have extremely high selectivity. For these circuits, detuning during cold weather can cause severe increases in loss.

One example of a coupling capacitor's dependence on temperature is illustrated in Fig 9. Different capacitors may have different characteristics. Variations in most modem coupling capacitors are not this severe. Manufacturers can provide data on new coupling capacitors at the time of purchase if requested to do so.

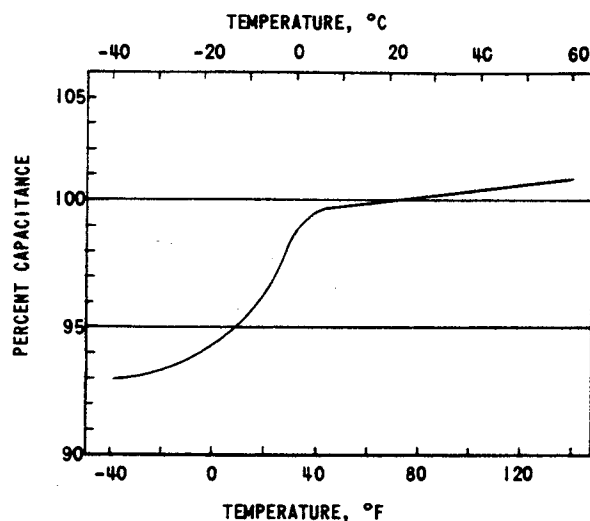


Figure 9—Typical Effect of Temperature on a Coupling Capacitor

3.5.6.6 Shunt Losses

Shunt losses are the losses due to the transmission of the PLC down undesired paths. These losses normally occur at the points where signals are coupled to the power line and are usually small when a proper line trap is used. For design purposes, a shunt loss of 1 dB at each end of a line is a reasonable estimate.

If the value of shunting impedance is known, shunt loss can be determined accurately by the formula

$$\text{shunt loss} = 10 \log \left| \frac{Z + Z_S}{Z_S} \right| (\text{dB}) \quad (8)$$

where

Z = nominal circuit impedance
 Z_S = shunting impedance

3.6 Modal Analysis

3.6.1 General

The development of long EHV transmission lines with transpositions has generated new problems for the carrier communications engineer. In the past, when lines were short, general rules of thumb were applied to carrier applications. If the actual attenuation varied as much as 30–50% from the expected value it was not serious, since there was a large margin of transmitter power and receiver sensitivity. The advent of long EHV lines dictates a more accurate

approach to PLC analysis, since it is not desirable to increase transmitter power, and the need still exists to predict the PLC channel performance in advance of line construction. Modal analysis is a mathematical tool that provides a more accurate analysis of carrier propagation, much like symmetrical components provide a method for analysis of unbalanced three-phase systems. Modal analysis is not only a mathematical tool, but it can also be readily identified in the physical world. The following discussion of modal analysis will center around the physical aspects. Excellent treatments of the analytical aspects are available [11], [12].

3.6.2 Description

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

$$V_x = V_s e^{-\gamma x} \quad (8A)$$

$$I_x = \frac{V_x}{Z_0} \quad (8B)$$

where

V_s = sending-end voltage
 Z_0 = characteristic impedance
 x = distance from sending end, in miles or kilometers (km)
 V_x, I_x = voltage and current at distance x from sending end
 γ = propagation constant

The propagation constant is composed of two quantities:

$$\gamma = \alpha + j\beta \quad (8C)$$

where α is an attenuation constant in nepers per mile (or nepers per km) and β is a phase constant in radians per mile (or radians per km). (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 the above equation. 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:

$$[V] = [V_s] e^{-[\gamma_m]x} \quad (9)$$

where m is an arbitrary integer to identify the modes. The solution of the above matrix equation will yield the voltage and current relationship of the modes. Each mode has its own 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.