POWER LINE CARRIER CHANNEL & APPLICATION CONSIDERATIONS FOR TRANSMISSION LINE RELAYING

by

Miriam P. Sanders
Product Manager

&

Roger E. Ray
Vice President

Pulsar Technologies, Inc.
4050 NW 121 Avenue
Coral Springs, FL
954-344-9822
www.pulsartech.com

Pulsar Document Number
C045–P0597

POWER LINE CARRIER CHANNEL & APPLICATION CONSIDERATIONS FOR TRANSMISSION LINE RELAYING

by
Miriam P. Sanders & Roger E. Ray

Introduction

While the application of Power-Line Carrier is not new to the power utility industry, the people who have historically worked on this type of equipment are leaving the industry, thereby creating a tremendous void in the expertise available. This paper is a tutorial that will present the basic principles of Power-Line Carrier to assist engineers who are new to this field as well as provide some good reference material for those experienced individuals who desire refresher information. It will focus on the application of carrier in Protective Relaying schemes.

History of PLC

Power Line Carrier (PLC) has been around longer than you think. For example, at the turn of the 20th century, a 500 Hz signal on the power line was used to control the street lights in New York City. The transmitters and receivers were originally powered with M-G (motor-generator) sets with a tuning coil 3 feet in diameter. As technology progressed, so did the PLC equipment. There are still many transmitters and receiver sets in use today that utilize vacuum tubes, or discrete transistor logic but these are being replaced with state of the art components such as digital signal processors and other VLSI components.

Today's Usage

100 years later, the power industry still uses PLC. Although its use is expanding into the distribution area for load control and even into households for control of lighting, alarming and a/c and heating, the major application is on Transmission Lines in Protective relaying. A channel is used in line relaying so that both ends of a circuit are cleared at high speed for all faults, including end zone faults. A PLC channel can also be used to provide remote tripping functions for transformer protection, shunt reactor protection and remote breaker failure relaying.

The typical application in the United States is with dedicated power line carrier, which means that one channel is used for protective relaying only. Single-sideband is used extensively in Europe and in "emerging growth countries" where many functions (relaying, voice, data, etc.) are multiplexed at the audio level (1200 to 3000 Hz) over a single RF channel (30 to 500 kHz). The trend in Europe is now changing towards dedicated carrier for relaying because fiber is taking over for generalized communications.

Goals

Many factors will affect the reliability of a power line carrier (PLC) channel. The goal is to get a signal level to the remote terminal that is above the sensitivity of the receiver, and with a signal-to-noise ratio (SNR) well above the minimum, so that the receiver can make a correct decision based on the information transmitted. If both of these requirements are met then the PLC channel will be reliable. The factors affecting reliability are:

- The amount of power out of the transmitter.
- The type and number of hybrids required to parallel transmitters and receivers.
- The type of line tuner applied.

- The size of the coupling capacitor in terms of capacitance.
- The type and size, in terms of inductance, of the line trap used.
- The power line voltage and the physical configuration of the power line.
- The phase(s) to which the PLC signal is coupled.
- The length of the circuit and transpositions in the circuit.
- The decoupling equipment at the receiving terminal (usually the same as the transmitting end).
- The type of modulation used to transmit the information, and the type of demodulation circuits in the receiver.
- The received signal-to-noise ratio (SNR).

The above list may not be all inclusive, but these are the major factors involved in the success or failure of a PLC channel. The paper will deal with each one of the above items in detail, and then use this information to design a reliable power-line carrier channel using an example.

Reliability

Reliability is a two-edged sword. In the Protective relaying world, we speak of reliable systems as being dependable or secure. The ultimate system would be both 100% dependable and 100% secure but this is nearly impossible to obtain. The definition of secure is that it will not falsely operate for an external fault whereas dependable means that it will trip correctly for an internal fault. Under the section "Typical Relaying Schemes using Power Line Carrier", we will explore reliability further.

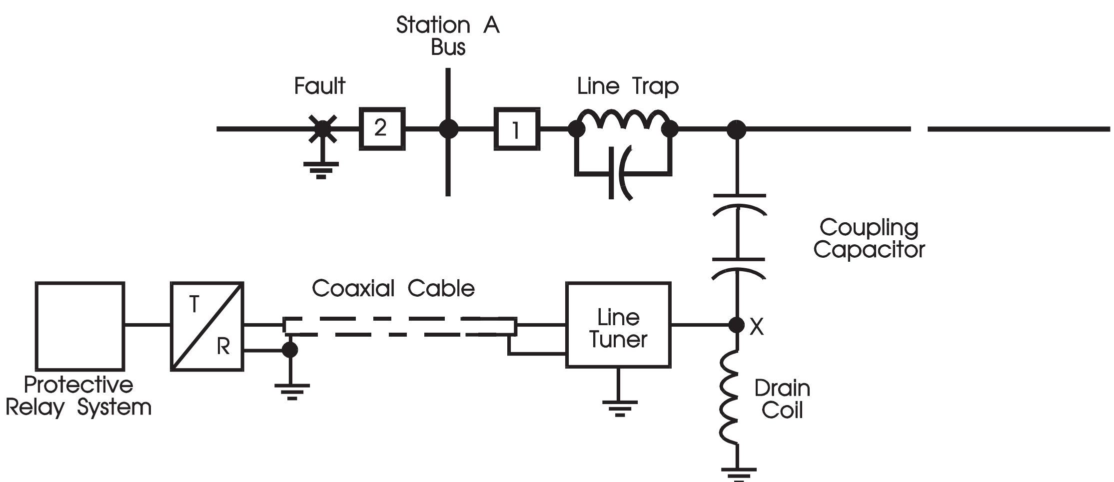

Figure 1. Basic Power Line Carrier Terminal

Major System Components Equipment

The major components of a PLC channel are shown in Figure 1. The problem associated with the PLC channel is the requirement to put the carrier signal onto the high voltage line without damaging the carrier equipment. Once the signal is on the power line it must be directed in the proper direction in order for it to be received at the remote line terminal.

Transmitters & Receivers

The carrier transmitters and receivers are usually mounted in a rack or cabinet in the control house, and the line tuner is out in the switchyard. This then means there is a large distance between the equipment and the tuner, and the connection between the two is made using a coaxial cable. The coaxial cable provides shielding so that noise cannot get into the cable and cause interference. The coaxial cable is connected to the line tuner which must be mounted at the base of the coupling capacitor. If there is more than one transmitter involved per terminal the signal must go through isolation circuits, typically hybrids, before connection to the line tuner.

Hybrids & Filters

The purpose of the hybrid circuits is to enable the connection of two or more transmitters together on one coaxial cable without causing intermodulation distortion due to the signal from one transmitter affecting the output stages of the other transmitter. Hybrids may also be required between transmitters and receivers, depending on the application. The hybrid circuits can, of course, cause large losses in the carrier path and must be used appropriately. High/low-pass and band-pass networks may also be used, in some applications, to isolate carrier equipment from each other.

Line Tuners

The purpose of the line tuner in conjunction with the coupling capacitor is to provide a low impedance path for the carrier energy to the transmission line and a high impedance path to the power frequency energy. The line tuner/coupling capacitor combination provides a low impedance path to the power line by forming a series resonant circuit tuned to the carrier frequency. On the other hand, the capacitance of the coupling capacitor is a high impedance to the power frequency energy. Even though the coupling capacitor has a high impedance at power frequencies, there must be a path to ground in order that the capacitor may do its job. This function is provided by the drain coil, which is in the base of the coupling capacitor. The drain coil is designed to be a low impedance at the power frequency and because of its inductance it will have a high impedance to the carrier frequency. Thus the combination of the line tuner, coupling capacitor, and the drain coil provide the necessary tools for coupling the carrier energy to the transmission line and blocking the power frequency energy. One last function of the line tuner is to provide matching of impedance between the carrier coaxial cable, usually 50 to 75 ohms, and the power line which will have an impedance of 150 to 500 ohms.

Line Traps

The carrier energy on the transmission line must be directed toward the remote line terminal and not toward the station bus, and it must be isolated from bus impedance variations. This task is performed by the line trap. The line trap is usually a form of a parallel resonant circuit which is tuned to the carrier energy frequency. A parallel resonant circuit has a high impedance at its tuned frequency, and it then causes most of the carrier energy to flow toward the remote line terminal. The coil of the line trap provides a low impedance path for the flow of the power frequency energy. Since the power flow is rather large at times, the coil used in a line trap must be large in terms of physical size.

Once the carrier energy is on the power line, any control of the signal has been given over to nature until it reaches the other end. During the process of traveling to the other end the signal is attenuated, and also noise from the environment is added to the signal. At the receiving terminal the signal is decoupled from the power line in much the same way that it was coupled at the transmitting terminal. The signal is then sent to the receivers in the control house via the coaxial cable.

The application of each of the components of the PLC channel must be considered carefully in order that the system operate properly. The examination of each of these components and the details of their

application will be discussed in the following sections. Then an example will be given to show the calculation of PLC performance.

Hybrids & Filters

Balanced

Resistive

There are many forms of hybrids, such as resistive hybrids, reactance hybrids, and skewed hybrids to name the most popular types. Simply stated a hybrid is a bridge network. The complete bridge is made up of components internal to the hybrid and the external circuits connected to the hybrid. It is best to explain how a hybrid operates by using the resistive hybrid as the example. Refer to Figure 2. The hybrid, in this case, is made of a resistor of 25 ohms, and a transformer with a center tap on the primary. The transformer turns ratio is √2/1 with the √2 turns on the center tapped primary. Let's assume the secondary of the transformer is terminated with a 50 ohm resistor and a voltage (V) is applied to input port #1. The 50 ohm load will be reflected in the primary of the transformer as a 25 ohm quantity from point (a) to the center tap (ct). This is because there is 1 turn on the primary, (a) to (ct), for every √2 turns on the secondary. The impedance will be transferred as the square of the turns ratio which in this case is 2 to 1. The voltage V will divide equally between the 25 ohm resistor and the 25 ohm reflected load into the top half of the primary. Thus each voltage has a value of V/2, and in the direction as shown. Since the center tapped primary of the transformer will act as an autotransformer, a voltage V/2 will also appear on the other half of the primary between point (ct) and (b). The voltage appearing across input port #2 due to the voltage V at input port #1 is the sum of the voltages around the loop from (g) to (y). As shown in Figure 2, this resultant voltage is 0 volts, and the hybrid isolates the voltage at one input port from the other input port. This isolation expressed in decibels is called trans-hybrid loss and is the same as return loss. Return loss is the ratio in decibels of the power into a discontinuity to the power reflected from the discontinuity. In terms of impedance this would be the ratio of sum of the impedances to the difference of the impedance. The reciprocal of this impedance ratio is call the reflection coefficient.

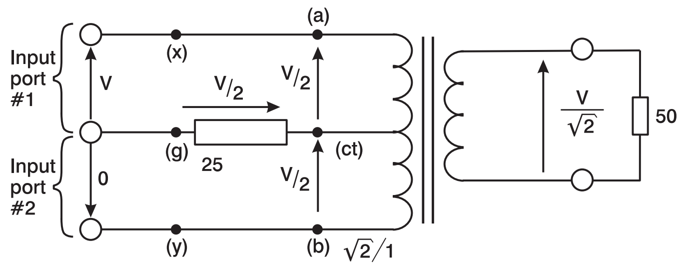

Figure 2. Resistive Hybrid

The mathematical expressions are:

$$\text{Reflection Coefficient} = \frac{R - R_T}{R + R_T} \quad \text{and}$$

$$\text{Return Loss} = 20 \log \frac{R + R_T}{R - R_T}$$

where R_T is its terminating resistance and R is the designed impedance.

A price must be paid for this isolation, and that is attenuation of the carrier signal from either input port to the output port. This loss is the ratio of the input voltage V and the output voltage *V/√2*, expressed in dB. The result of this calculation will be 3 dB. However, the transformer will have some losses and the loss from input to output will be on the order of 3.5 dB for most hybrids of the type shown in Figure 2. The

difference in decibels between the input power to a device and the output power of the device is the insertion loss. This can be expressed as follows:

$$\text{Insertion Loss} = 10 \log \frac{P_i}{P_o} \text{ or } 20 \log \frac{V_1}{V_2}, \text{ where Z is equal.}$$

If the reader were to go through an analysis of the hybrid shown in Figure 2 using a termination of 45 ohms, the results would be different than discussed above. That is, the voltage will *not* divide equally between (a) to (ct) and (ct) to (g) and a resultant voltage will appear across input port #2. Thus the hybrid can only provide the best isolation when it is properly terminated, in this case, with a 50 ohm resistor. It is then appropriate to only apply a non-adjustable hybrid in an area of known termination. In cases where there is a termination of 45 ohms, the trans-hybrid loss (return loss) will be:

$$20 \log \left[\frac{50 + 45}{50 - 45}\right] = 25.6 \text{ dB}$$

Adequate return loss is 30 dB or greater.

Reactance

When a hybrid is connected to the power line through a line tuner and coupling capacitor the termination impedance may not always be a 50 Ω resistive. Therefore, the hybrid which is connected to the tuner should be an adjustable type and should be designed to handle non-resistive terminations in order to obtain the best performance.

This type of hybrid is called a reactance hybrid and is shown in Figure 3. Note that the transformer has impedance matching taps to adjust to different magnitudes of termination. The balance network is no longer a simple resistor, as in the resistance hybrid, but a resistor, inductor, and capacitor. This is to enable the hybrid to adjust to non-resistive loads. The reactance hybrid will also use an impedance matching transformer similar to the one used by resistive hybrids.

Balanced hybrids have equal losses from each input port to the output port. The success of a PLC channel will depend on the received SNR, and this can be obtained by maximizing the amount of transmitter signal that is coupled to the phase wire.

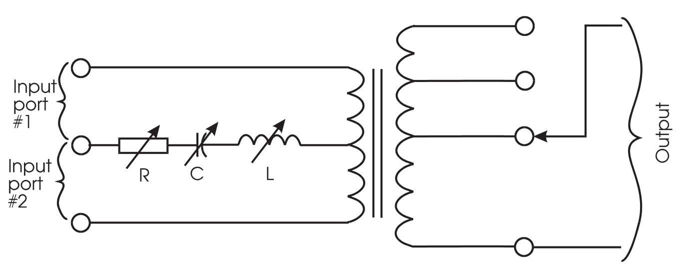

Figure 3. Reactance Hybrid

Unbalanced (Skewed)

It is desirable to use balanced hybrids in most applications, but there may be other factors to consider on long lines where losses may be high. Another type of hybrid can be used in an application of this type. It is called a skewed hybrid. Its name comes from the fact that the losses from input port #1 to the output are not the same as the losses from port #2 to the output. The skewed hybrid may be designed with different magnitudes of unbalance, but the most common is 0.5/12 dB. That is, the loss from input port #1 (transmit port) and the output is 0.5 dB and the loss from output port to the input port #2 (receive port) is 12 dB. The skewed hybrid then allows the transmitter to be isolated from the receiver with only a 0.5 dB loss instead of the 3.5 dB loss of the balanced hybrid. Thus twice as much transmitter power (3 dB) is applied to the line, and the SNR will be improved by 3 dB. The high losses in the receive path do not affect the SNR since the noise is attenuated by the same amount as the signal. The skewed hybrid will generally have an impedance matching network with a fixed balance network and would be considered a resistive type hybrid. When using a skewed hybrid, the receiver port must be terminated in 50 ohms.

L/C Filters

While not providing the isolation of a hybrid, L/C filters may be used to combine two or more transmitters. The bandwidth response of the series resonant L/C filter is a function of the L:C ratio and the frequency to which it is tuned. The insertion loss of the L/C filter is typically around 2 dB, while the return-loss is only around 10 to 15 dB, depending on application. Another disadvantage of the L/C filter is the tuning required during installation dictates accurate tuning to maintain the needed isolation.

Minimum frequency separation of the transmitters should be 25 kHz or 10% of the highest frequency. These would typically be used where hybrids could not be applied. However, one should calculate the isolation resulting from use of a resistive hybrid as compared to the LC unit. A mistermination of a resistive hybrid of anywhere from 25 to 100 ohms will produce a 10 dB or greater return loss. The advantage here would be not having to tune a LC unit.

Coaxial Cables and Lead-in Conductor

Coaxial cables are used to connect the carrier sets (usually in the control house) to the line tuners in the switchyard. The lead-in conductor is used to connect the line tuner to the coupling capacitor.

Coaxial Cable

Coaxial cable is normally used between a line tuner and a transmitter/receiver or between line tuners in a long bypass to provide a low impedance connection. Connections between hybrids also use coaxial cables. The copper braid forms an RF shield which should be grounded at the transmitter/receiver end only, or at only one end of a bypass. By grounding only one end of the shield you eliminate problems during faults due to ground potential rise (GPR) conditions. GPR currents can saturate the impedance-matching transformer and cause a loss of the carrier channel.

The typical coaxial cable is RG-8/U with a center conductor of 7 strands of No. 21 copper wire forming an AWG 12 conductor and a braided shield made of AWG No. 36 copper strands. The outer covering is a polyvinyl plastic jacket. The characteristic impedance of RG-8/U cable is 52 Ω. The attenuation versus frequency for this cable is shown in Table I for 1,000 feet.

The most common polyvinyl compound used for jacket material is polyvinyl chloride (PVC). Although this material has excellent chemical and abrasion resistance, better moisture resistance material such as black polyethylene (black PE), cross-linked polyethylene (XL-PE), or chlorinated polyethylene(CPE) are now available. Recent history has shown problems with the use of PVC as the jacket material due to its poor resistance to moisture.

Table I - Typical Attenuation Characteristics of RG-8/U

FREQUENCY (kHz)	LOSS (dB/1000 FEET)
30	0.38
50	0.44
100	0.55
150	0.66
200	0.77
300	0.90

Triaxial Cable

In areas, such as EHV lines, where larger ground fault current will induce greater ground potential rise, a triaxial cable can be used. This has a second braid to provide a second shield, insulated from the first shield. This second shield should be grounded at both ends. If the insulation between the two braids is too thin, the outer braid grounds the inner braid causing carrier problems.

Insulated Single Conductor Lead-in Wire

To connect the coupling capacitor to the line tuning equipment, use an insulated single conductor lead-in cable. Bare conductors should not be used for this application because it is possible to introduce excessive leakage to ground. Coaxial cable usage will introduce excessive capacitance. The connection between the line tuner and the coupling capacitor is a high impedance point in the series-tuned circuit formed by the tuning inductor and the coupling capacitor. Stray capacitance and leakage to ground will increase the losses of the tuner and affect the bandwidth. A cable rated at a high voltage and of sufficient size to maintain some rigidity is recommended.

Power Cable that is a single conductor, 0.61 inches (15.5 mm) in diameter, AWG #8, 7 strand copper conductor, rated 5 kV unshielded, for 90°C wet or dry service with either ethylene-propylene (EPR) or XL-PE insulation and a PVC jacket is typically used as lead-in cable.

To reduce the stray capacitance and leakage currents either of the following methods may be used:

1. The single conductor lead-in should be run as directly as possible between its required terminations. The conductor insulation should be unbroken between its ends to maintain low leakage. It should be supported on insulators and fed through entrance bushings into the coupling capacitor and the line tuner. Drip loops should be used as needed to divert water from entering the line tuner or coupling capacitor housings.
2. The insulated single conductor lead-in can be installed in a PVC or other plastic conduit which should be supported on stand-offs or insulators. If a significant part of the conductor's length is outside the conduit, it should be supported on insulators and fed through entrance bushings as noted above in (1).

The typical lead-in conductors is rated for 90°C conductor temperature continuously with emergency operation at 130°C; the PE-insulated coaxial and triaxial cables can operate at a maximum conductor of 80°C. If higher temperature operation is required, then a special cable with a high-temperature insulation such as silicone rubber or Teflon and perhaps a fiberglass jacket could be used, but such a cable would be very expensive.

Coupling Capacitors

The coupling capacitors will be discussed before the line tuners since they play a large part in the response of the line tuner. In fact the coupling capacitor is used as part of the tuning circuit. The coupling capacitor is the device which provides a low impedance path for the carrier energy to the high voltage line, and at the same time blocks the power frequency current by being a high impedance path at those frequencies. It can only perform its function of dropping line voltage across its capacitance if the low voltage end is at ground potential. Since it is desirable to connect the line tuner output to this low voltage point a device must be used to provide a high impedance path to ground for the carrier signal and a low impedance path for the power frequency current. This device is an inductor and is called a drain coil. The coupling capacitor and drain coil circuit are shown in Figure 4.

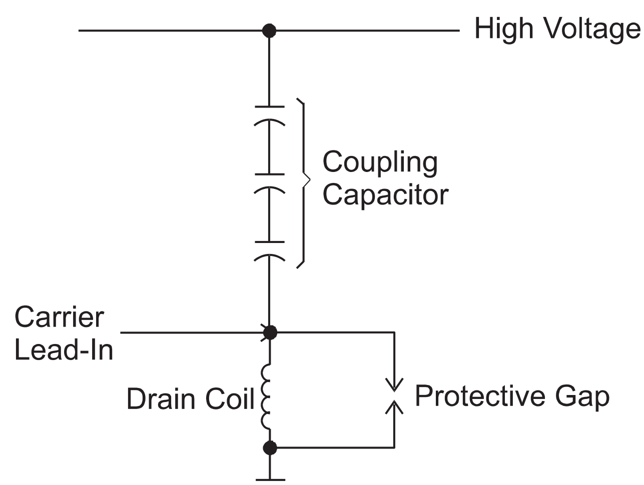

Figure 4. Coupling Capacitor & Drain Coil Combination

It is desirable to have the coupling capacitor value as large as possible in order to lower the loss of carrier energy and keep the bandwidth of the coupling system as wide as possible. However, due to the high voltage that must be handled and financial budget limitations, the coupling capacitor values are not as high as one might desire. Technology has enabled suppliers to continually increase the capacitance of the coupling capacitor for the same price thus improving performance. Depending on line voltage and capacitor type, the capacitance values in use range from 0.001 to .05 microfarads.

Line Tuners

In conjunction with the coupling capacitor, the line tuner provides a low loss path to the power line for the carrier signal. There are two basic types of line tuners, resonant and broad-band. The type used depends on the transmission line and the number of carrier channels to be placed on the line.

The line tuner should be mounted either in the base of the coupling capacitor, if space is available, or on the structure that supports the coupling capacitor. The reason is that the lead between the coupling capacitor and tuner should be as short as possible. Since the coupling capacitor is part of the filter circuit, the point of connection between it and the line tuner is generally a high impedance point. Any capacitance to ground in the connecting cable will cause losses and change the tuning circuit characteristics. This cable is typically a single conductor that is insulated for high voltage and has a very low shunt capacitance to ground. As mentioned before, coaxial cable should not be used for this connection.

Of the resonant type tuners there are two that are widely used. These are single-frequency and double-frequency, and are used for carrier systems which have one group or two groups of channels with narrow bandwidth requirements, respectively.

All line tuners will have a protector unit which is connected from the output lead to ground. This protector unit must consist of a grounding switch and a protective gap. The gap is present to protect the tuner from failure during large transients on the power line. These transients have large amounts of high frequency energy which is passed by the coupling capacitor and are present at the tuner because the drain coil is a high impedance to these frequencies. The grounding switch is for personnel protection during maintenance. Sometimes the line tuners are supplied with a drain coil in addition to the one supplied in the coupling capacitor. This drain coil should not be considered as the primary drainage path. The coupling capacitor must always have a drain coil and it is considered the primary drainage path for power frequency currents.

Resonant-Single Frequency

The single-frequency tuner, shown in Figure 5, has a single inductor and a matching transformer. The inductor is arranged so that it and the coupling capacitor form a series resonant circuit. When this circuit is tuned to the carrier frequency it will provide a low impedance path for the carrier signal to the power line. The matching transformer provides the impedance match between the 50 or 75 ohm coaxial cable and the characteristic impedance of the power line (150 to 500 ohms). This tuner will tune at one frequency, thus the name single-

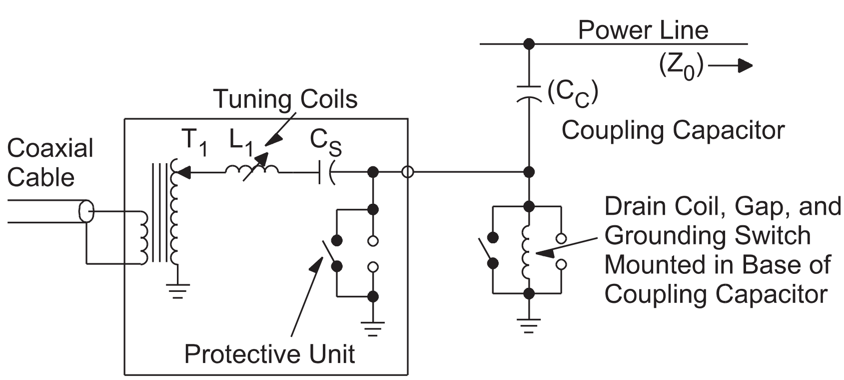

Figure 5. Single Frequency Line Tuner

frequency tuner. Figure 6 shows the frequency characteristics of the single frequency tuner.

Resonant-Double Frequency

The double-frequency tuner, on the other hand, has two sets of resonant circuits so it may be tuned to pass two frequencies to the power line. The two-frequency tuner shown in Figure 7 not only provides a low loss path for two frequencies, but it also isolates the two sets of carrier equipment from each other. As seen in Figure 7 there are two paths, each with its own matching transformer and series inductor, but each path also has a parallel LC circuit used for blocking the carrier signal from the other path. Each path is tuned to series resonance with the coupling capacitor at its given frequency, and the parallel LC circuits are tuned to resonate at the frequency passed by the other path. For the two-frequency tuners, the minimum frequency separation is generally 25 per cent of the lower frequency or 25 kHz, whichever is smaller. The frequency response curves for the two-frequency line tuners is shown in Figure 8.

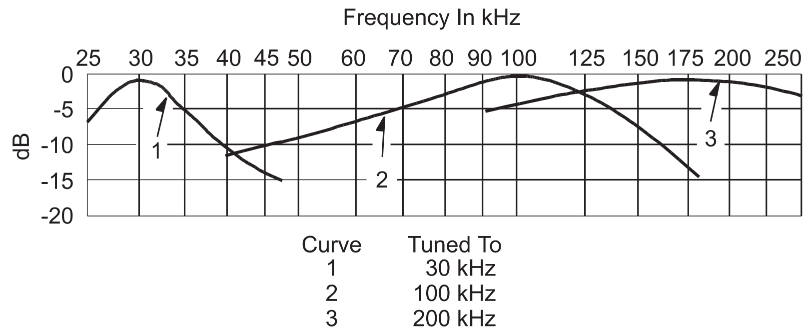

Figure 6. Single Frequency Tuner Characteristics

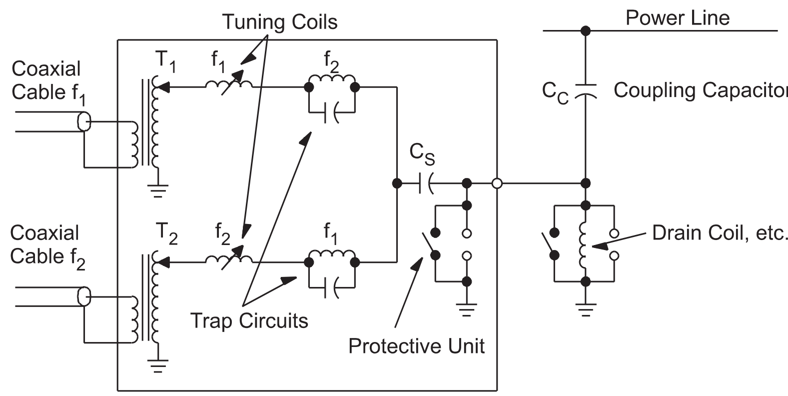

Figure 7. Double Frequency Line Tuner

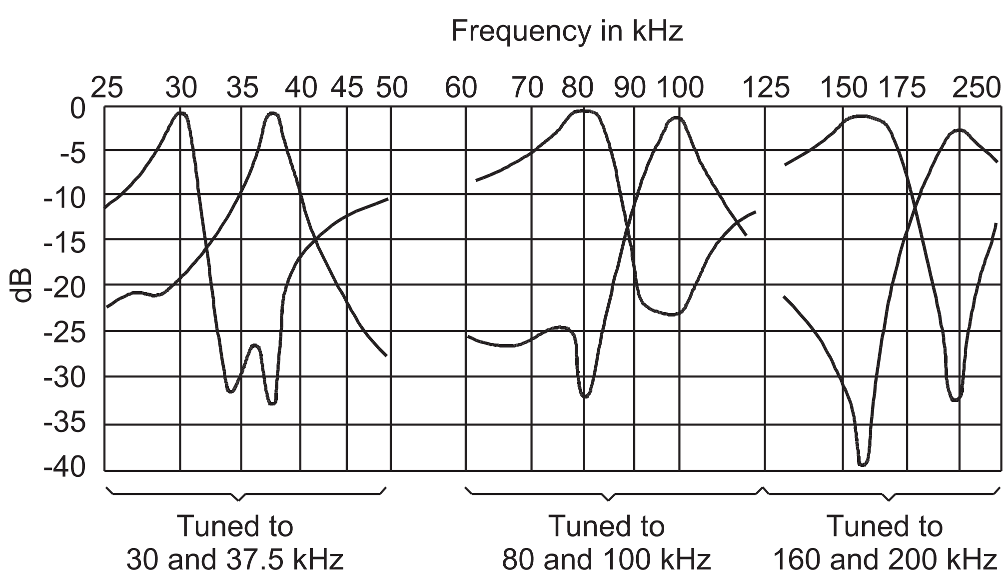

Figure 8. Typical Characteristics Double Frequency Line Tuner

Broad Band

If it is desired to place more than two narrow band frequency groups on the line then one must use broad-band coupling. There are two forms of broad-band coupling used: high-pass and band-pass tuners.

High-pass

The high-pass tuner is the simpler of the two and in most cases is the preferred type. It is usually small enough to fit in the base of the coupling capacitor and as a result does not need an extra outdoor cabinet. Another advantage of the high-pass tuner is that the high impedance lead to the coupling capacitor is very short and not exposed to the elements. The high-pass tuner is shown in Figure 9. The equivalent circuit for the high-pass tuner is shown in Figure 10. Note that the coupling capacitor is used as one of the series branches of the high-pass circuit. The low-frequency cutoff of the circuit is determined by the size of the coupling capacitor and the terminating impedance of the power line. The characteristic curves for the tuner are shown in Figure 11. One should not apply any carrier frequencies close to the cutoff frequency of the circuit since it does not have a stable characteristic impedance in that area. The high-pass tuner has one coaxial cable input. Therefore, all of the carrier sets must be paralleled using the principles described in the section on "Paralleling Transmitters & Receivers."

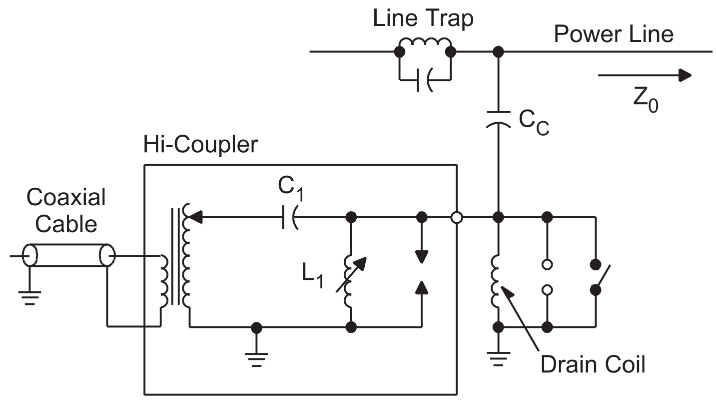

Figure 9. High Pass Tuner

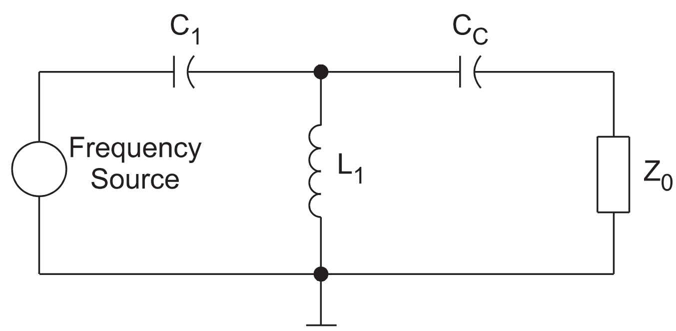

Figure 10. Equivalent Circuit of High Pass Tuner

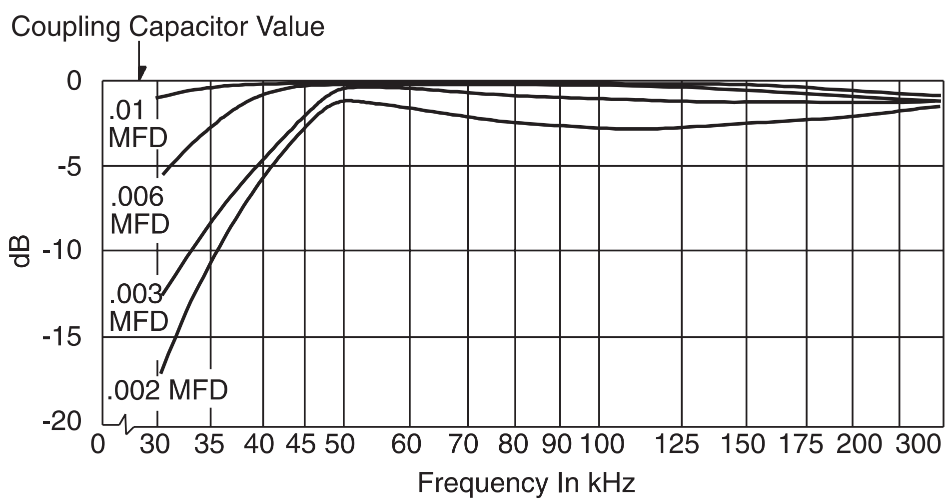

Figure 11. Typical Characteristics of a High Pass Tuner

Band-pass

A second form of wide-band coupling is the band-pass tuner. This tuner provides a large bandwidth with a constant coupling impedance over a band of carrier frequencies. The band-band tuner is shown in Figure 12. The bandwidth of the band-pass tuner depends on coupling capacitance, the terminating impedance, and the square of the geometric mean frequency(GMF) to which the filter is tuned. Figure 13 shows a graph of the typical bandwidth characteristics of the band-pass tuner. One should be careful in applying frequencies too close to the band edges of a band-pass tuner since this area can change with varying temperature and changes in standing waves which may be produced on the power line due to changes in line termination.

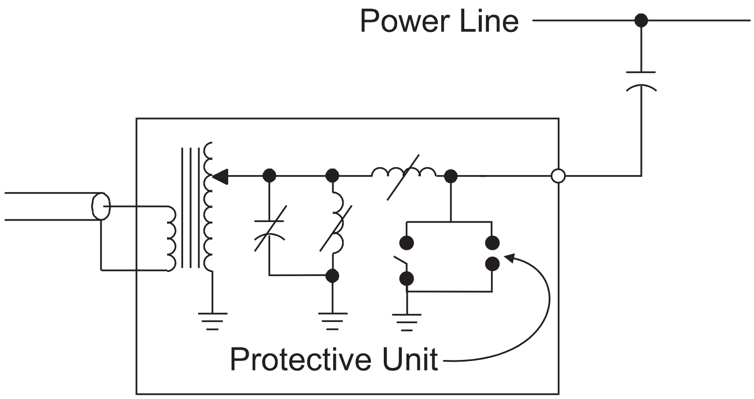

Figure 12. Band-Pass Tuner

Line Traps

When the carrier signal is coupled to the power line it can propagate in two directions, either to the remote line terminal or into the station bus and onto other lines. If the signal goes into the station bus much of its energy will be shunted to ground by the bus capacitance. Also some of this energy would propagate out on other lines thus transmitting the signal to a large portion of the system. This is undesirable since the same frequency may be used on another line. Because of these problems, a device is needed to block the energy from going back into the bus and direct it toward the remote line terminal. This device is called a line trap. The general design of a line trap is that of a parallel LC circuit. This type of a circuit presents a high impedance to the carrier signal at its resonant frequency. Thus if the parallel LC circuit were placed in series with the transmission line, between the bus and the coupling capacitor, then the carrier signal would propagate toward the remote terminal. The line trap must be capable of providing a very low impedance path to the power frequency current. The inductor in the trap provides this path, and it is designed to carry the large currents required. Another important function of the line trap is to isolate the carrier signal from changes in the bus impedance, thus making the carrier circuit more independent of switching conditions.

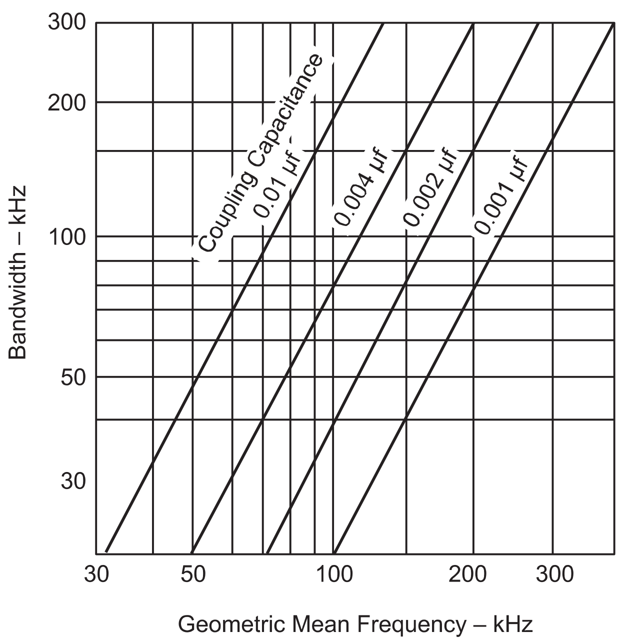

Figure 13. Typical Bandwidths of a Band-Pass Tuner

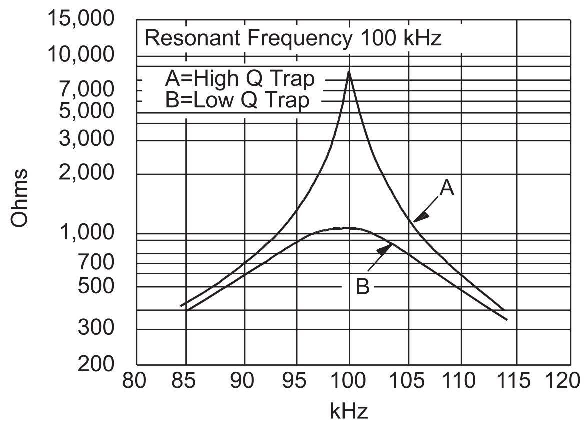

Figure 14.
Characteristic of Single Frequency Trap

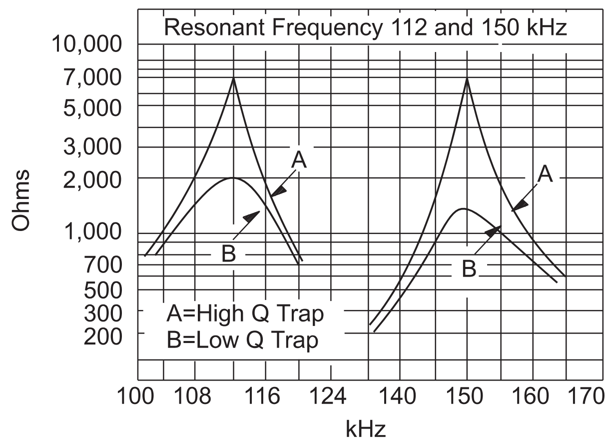

Figure 15.
Characteristic of Double Frequency Trap

Line traps come in several versions just as the tuners do, and these types are single-frequency, double-frequency, and band-pass. Usually the trap used is the same type as the line tuner, that is, if the tuner is a single-frequency type, the trap will also be a single-frequency type. However, it is not absolutely necessary that the line trap be of the same type as the tuner. As an example wide-band traps could be used at all times. The question of economics and blocking impedance will dictate the type of trap to be applied. Figure 14, Figure 15, and Figure 16 show the characteristics of the three types of traps. Note that both the single- and double-frequency traps have a rather sharp resonance peak which provides a 7,000 to 10,000 ohm blocking impedance at one given frequency. On the other hand, the wide-band trap shown will block a large bandwidth of frequencies but its blocking impedance is low, on the order of 500 ohms. Therefore, the resonant traps will have less losses than the wide-band type.

Single Frequency and Double Frequency

Figure 14 shows the typical characteristic for the single-frequency trap and Figure 15 shows double-frequency traps. The trap can have both a low-Q and a high-Q setting. The low-Q setting of the trap provides a lower blocking impedance, but has a wider bandwidth. This setting can thus be used to couple two or more very close frequencies to the line. The high-Q setting of the trap provides the normal high blocking impedance, but it has a very narrow bandwidth which may be very susceptible to variations in the bus impedance. The bus is capacitive at carrier frequencies and it can form a series resonant circuit with the inductance of the trap, and this then can create a low impedance path to ground. Power transformers on the line behind the trap have been known to affect the trap and change the tuning characteristic. These types of effects can be detected by comparing the received signal at the other end for two conditions. The first level is measured with the disconnect switch between the trap and the bus open. The second level is with the

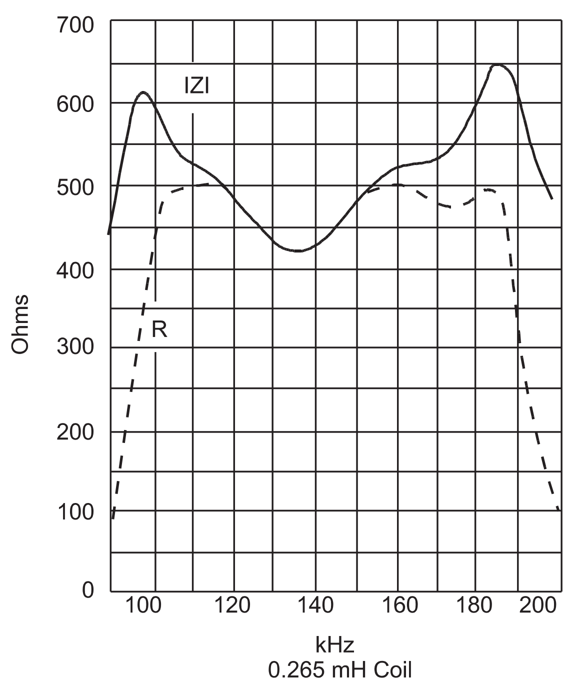

Figure 16. Characteristics of a Band-pass Trap

line normal (disconnect closed). If the signal level changes by a large amount between these two conditions and you are certain the trap is tuned properly, then the low-Q setting should be selected since the station impedance will have less effect on the trap tuning. The channel losses will be a little higher, but the channel will be less affected by switching conditions. Note, that not all traps have the low-Q option, and you should check with the manufacturer of the trap.

Wide-band

When applying a wide band trap, two things must be decided, that is, bandwidth requirements and how much blocking impedance is needed. Both these factors will greatly affect the cost of the trap. The blocking impedance and bandwidth are directly related to the required inductance which is a large part of the cost. Also it is suggested that frequencies not be used that are near the band edge of the trap because the tuning in that area may change with system conditions. Figure 16 shows the typical characteristic for the wide band trap.

Power Line Characteristics at RF

Carrier frequencies exceed power frequencies by a factor of 500 or more. As a result, a transmission line's response to carrier frequencies will be different from its response to power frequencies. At the power frequency, all power lines are electrically short in terms of wavelength. At carrier frequencies, however, most lines are many wavelengths long because of the much shorter wavelength. The (f_C) frequency to wavelength (λ) relationship is approximated by:

$$\lambda = \frac{0.98 * c}{f_C}$$

Remember that c= 3 x10^8 meters/seconds (speed of light) or 186,000 miles/second.

From this relationship it is clear that a 250 kHz signal will have a wavelength of 1,176 meters (0.73 miles). This means that a 100 Kilometer (62 mile) line will be 85 wavelengths long. At 60 Hz, this line will be only 0.02 of a wavelength long. Keep this in mind for the section on "Special Considerations."

Line Attenuation

Overhead Line

The relative efficiency of power- and carrier-frequency transmission also differs significantly. Many factors are involved in the carrier signal losses on a transmission line. The primary factors are: carrier frequency, line construction, phase conductor size and material, shield wire size and material, type and location of transpositions, weather conditions, earth conductivity, and insulator leakage. Line losses will increase as the frequency goes higher. This is primarily because of the fact that most losses are due to shunt capacitance which becomes a lower impedance at higher frequencies. Conductor losses also play a role in increasing attenuation, due to the increased skin effect which means that less conductor area is available to higher frequency current.

Weather conditions play a large role in the changing of the line attenuation with time. Losses will increase for all inclement weather conditions. The worst offender, however, is when heavy frost is formed on the line. Because of the skin effect, the carrier signal tries to propagate on the ice instead of the conductor. The attenuation can change as much as 4 or 5:1, depending on frequency. Also attenuation is increased on transmission lines due to the presence of contaminants on the insulators. The contaminants will have a much larger effect when it is raining than when the line is dry. The worse situation here is a light rain where the contaminants do not get washed off the insulators.

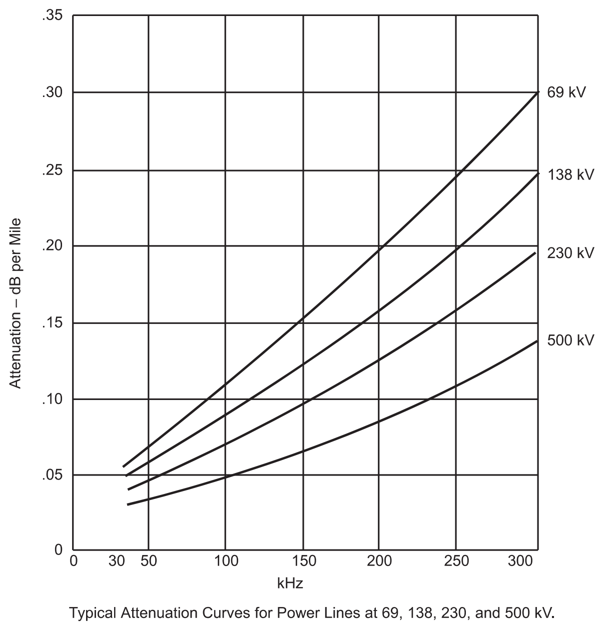

Figure 17. Transmission Line Losses

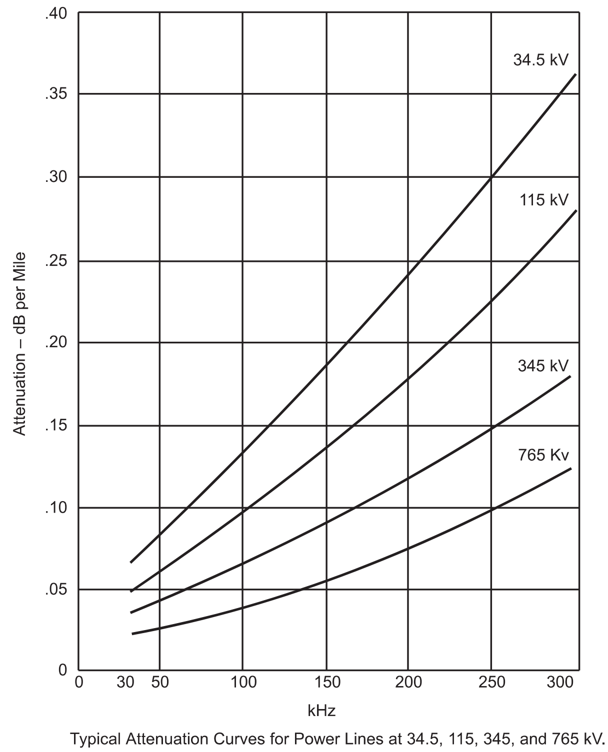

Figure 18. Transmission Line Losses

Line losses will change due to changing earth conductivity. This is particularly true when the coupling method relies on modes of propagation which require the earth as a return path. These kinds of earth conductivity changes come about by extreme changes in soil moisture. This may or may not be a concern, depending on the type of soil that is present. Typical fair-weather losses for transmission lines from 34.5 kV to 765 kV are shown in Figure 17 and Figure 18. As indicated in Table II, foul-weather losses are estimated by adding 25 percent to the values shown for lines 230 kV or higher, and 50 percent for lines less than 230 kV. The corrections for transpositions in the line are shown in Table III. The type of coupling will effect the overall line loss and Table IV shows the coupling correction factors for the most popular coupling arrangements. Coupling types are generally described on the basis of a single circuit line of flat construction. First, there are the single phase to ground types, that is, the carrier signal is coupled between one phase and ground. Of these types the

Table II – Correction Factors for Foul-Weather

34-138 kV	Add 50 %
230-765 kV	Add 25%

Table III – Transposition Losses in dB for 345 kV & Higher

Number	<10 Mi. *	>100 Mi. *
1	0	6
2-4	0	8
5 or more	0	10

**Use Linear Interpolation for loss between 10 & 100 mi.*

Table IV – Coupling Correction Factors

Type of Coupling*	>50 mi. Line
Mode 1	0
Center-to-Outer Phase	2
Center-to-Ground	
Al or Cu Ground Wire	3
Steel Ground Wire	6
Outer-to-Outer (In Phase)	5

**Unused phases assumed to be at rf ground.*

most popular is center phase to ground. Next there are the phase-to-phase coupling types. In this type the carrier signal is coupled between two phases of the power line, and the energy in the two phases are out of phase with each other, in most cases. The last form of coupling is called mode 1 and is a special case of coupling to all three phases. In mode 1 coupling, current is in phase on the two outside phases and returns through the center phase. mode 1 coupling is the most efficient means of coupling the carrier to the power line. Overall system losses will be discussed later by using an example. For a more extensive explanation of mode 1 coupling see the section titled “Modal Analysis.”

Power Cable

Line attenuation in a power cable is larger than those seen in overhead phase wires. The specific loss encountered with a particular cable will depend on its construction and the method of coupling. Two types found are single-conductors self-contained and single or three-conductor pipe-type cables. Skid wires wrapped around the conductors, which protect the conductors during insertion, will affect the attenuation of the carrier signal as well. Figure 19 shows some representative values for a single phase to ground coupled. Mutual coupling between phases in a three-conductor pipe-type cable will vary with frequency. Also, if the cable is three-single-conductor pipe-type cables, mutual coupling will not exist. This must be considered when designing the system since this will affect the efficiency of coupling and during faults will adversely affect the channel performance. That is if the fault is on the coupled phase, no signal will get through the fault since there is no mutual coupling to the other phases.

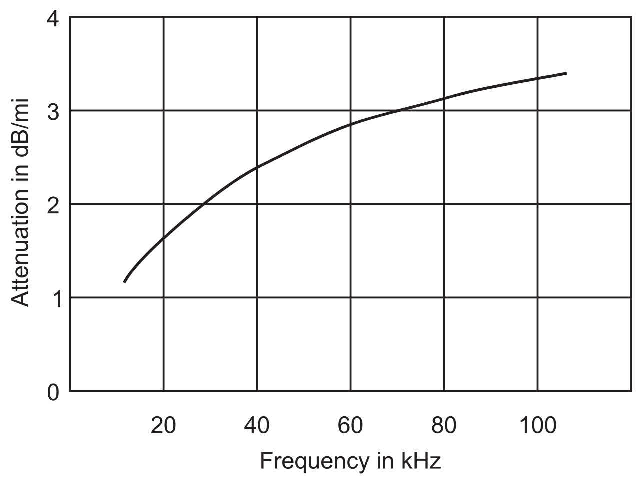

Figure 19. Phase-to-Ground Attenuation on a 138 kV Pipe-Type Cable

Characteristic Impedance

The characteristic impedance [1] of a transmission line is defined as the ratio of the voltage to the current of a traveling wave on a line of infinite length. This ratio of voltage to its corresponding current at any point the line is a constant impedance, Z_0. Carrier terminals and line coupling equipment must match the characteristic impedance for best power transfer.

$$Z_0 = \frac{V^+}{I^+} = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

In practice, the $j\omega C$ and $j\omega L$ are so large in relationship to R and G, this equation can be reduced to :

$$Z_0 = \sqrt{\frac{L}{C}}$$

By applying appropriate formulas for L and C, this equation can be expressed in terms of the distance between conductors and the radius of the conductor as follows:

$$Z_0 = 276 \log \frac{D}{r}$$

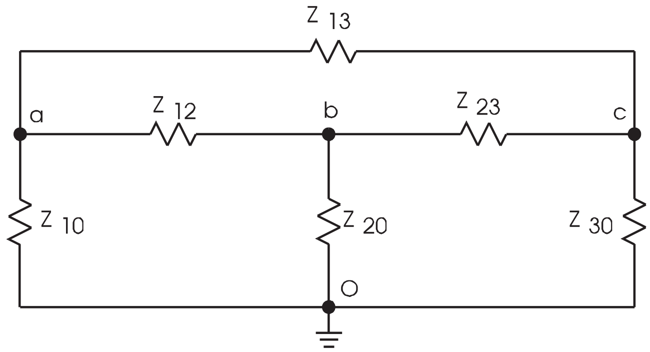

Figure 20. Terminating Network for a Three-Phase Line

The characteristic impedance will vary according to the distance between conductors, distance to ground, and the radius of the individual conductor. In general, both the radius of the conductors and distance between conductors increase with higher voltages, so there is little variance of characteristic impedance at various voltages. When bundled conductors are used, as in Extra-high voltage (EHV) transmission lines, the effective impedance will be lower.

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 through the line were infinitely long. To do this would require a network of 6 impedances for a three phase line as shown in Figure 20. Since this is never done, the impedance seen by the coupling equipment is affected by the reflected energy on the uncoupled phases.

Overhead Line

Overhead lines are the predominate choice for transmission lines. Table V shows the range of characteristic impedance values for a variety of lines, including bundled conductor lines.

Table V – Range of Characteristic Impedances for PLC Circuits on Overhead Lines

Transmission Line Conductor (Each Phase)	**Characteristic Impedance (ohms)**	
	Phase to Ground	Phase to Phase
Single Wire	350-500	650-800
Bundled (2-wire)	250-400	500-600
Bundled (4-wire)	200-350	420-500

Power Cable

The characteristic impedance of power cables (underground) vary greatly from those for overhead lines. Generally speaking, the power cables will have a characteristic impedance between 10 to 60 Ω.

Power Line Noise

One of the factors which limit the distance of a PLC channel is the noise on the power line, and it must be considered in the design of a PLC channel. The channel must be designed such that the received signal level is greater than the received noise level in the band of the carrier receiver. How much greater will depend on the type of modulation and application of the channel. As far as relaying is concerned, the effect of a poor SNR may either be a failure to trip or a false trip, both of which are undesirable responses. The study of noise on power lines is a major subject, but some of the causes and effects will be discussed.

There are two basic types of power line noise, continuous noise and impulse noise. Continuous noise will be present at all times and its amplitude will vary slowly with respect to the frequency considered, and impulse noise will exist for only short periods of time. The impulse noise will have an amplitude much greater than the average level of the continuous noise. Both types of noise consist of frequencies that cover

the power line carrier band, and many times both types can be considered as white noise over the bandwidth of a carrier receiver. White noise is defined as noise having a level power density spectrum for all frequencies and an amplitude function which is considered to be random with time. For the purposes of calculating SNR and channel performance, the noise will be considered to be white noise. One can expect to obtain overall channel performance information in this way, but it should be kept in mind that impulse noise may have other effects.

Much of the noise on the power line is impulsive in nature. This is because the noise is generated by corona discharge which occurs every half cycle of the power frequency, and the levels are generally below the levels of the carrier signals. The impulses are, however, smoothed out by the input filter of the receiver and as a result can be considered as white noise to the demodulating circuits. It is important to note that very large impulses of noise, such as those created by a disconnect switch operation, will have a very different effect on the carrier receiver. These large impulses will shock excite the input filters and cause the filters to ring, thus the receiver creates, in effect, added in-band noise over and above the in-band noise present in the impulse. The nature of the energy of the ringing is dependent on the type of filter and at what frequency the least insertion loss occurs in the pass band.

With the advent of High Voltage dc transmission lines came a new type of noise in the PLC environment. As the valves fire in the conversion process from dc to ac and vice versa, they produce a noise whose level is inversely proportional to frequency. That is, it is high at the low end of the PLC frequency spectrum. This requires filtering to reduce this noise to an acceptable level. The converters have been known to produce frequencies just below the carrier band which even though they are low will create serious problems with certain types of PLC terminal equipment. These frequencies can be series resonant with the coupling capacitor and the drain coil. In general, this will not cause a problem except in the case of older drain coils which have an iron core. The large currents developed because of the series resonance causes the drain coil to saturate and thus shorts the desired carrier to signal ground. The effects of this type of noise can be seen many line sections away from the converters. Therefore, it is a good idea to check if the harmonics from a converter station are series resonant with a given coupling capacitor/drain coil combination.

Foul weather will have a great effect on line noise. Thunderstorms produce discharges which can briefly increase line noise. Also a large increase in noise is due to the increase in corona noise during wet conditions. This level of noise may be as high as 30 dB above the fair weather noise.

Since relay channels must operate during fault conditions it is of interest to know what noise is generated during the fault. A power arc will not generate noise once the arc is established[6]. However, when the arc first strikes the noise energy can be very severe for the first 1 to 4 ms, and after this time the air becomes a conductor and the noise generated is small. In fact the noise during the fault may be less than the pre-fault noise since in most cases the voltage on the line is depressed and as a result corona discharge will be less.

Figure 21 shows the typical fair- and foul-weather average noise levels for a 230 kV line and a 3 kHz bandwidth. The dBm of the horizontal scale is dB referenced to 1 milliwatt.

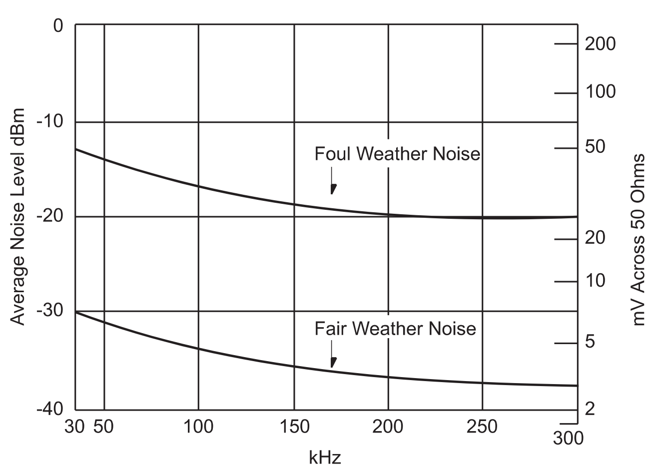

Figure 21. Typical Average Noise Levels on a 230 kV Line in a 3 kHz Bandwidth

For convenience, a millivolt scale is shown on the right side. To determine line noise levels at other system voltages use the appropriate correction factor from Table VI. When calculating the SNR you must take into account the actual bandwidth of the channel since only the noise passing through the channel bandwidth causes a problem. The noise level must then be corrected for bandwidth, and several different bandwidth correction factors are shown in Table VII. The general form of the correction in dB is given below:

$$dB = 10\ Log_{10}\left(\frac{BW}{3000}\right)$$

Where BW is the bandwidth of the channel being used.

Table VI – Correction Factors for Noise for Voltages Other Than 230 kV in

Voltages (kV)	Correction Factor (dB)
66-115	-8
138-161	-4
230	0
345*	+2
500*	+5
765*	+12

**Bundled conductors*

To obtain the final SNR, the correction factors shown in Table VI and Table VII should be added to the noise level obtained from Figure 21. If the channel bandwidth is less than 3,000 Hz then the correction is negative and the noise level is less, and if it is positive then the bandwidth is greater than 3,000 Hz, thus the noise level increases. As an example let's assume a receiver is operating at 100 kHz on a 345 kV line with a bandwidth of 600 Hz. The basic foul weather noise level from Figure 21 is -17 dBm. The correction factor for the voltage level at 345 kV from Table VI is +2 dB. The correction factor for bandwidth will be:

Table VII – Bandwidth Correction Factors for Bandwidths other than 3 kHz

Receiver Equipment	Bandwidth (Hz)	Correction Factor (dB)
Wide band	1200	-4
Medium band	600	-7
Narrow band	300	-10

$$dB = 10\ Log_{10}\left(\frac{600}{3000}\right) = -7\ dB$$

Thus the noise level that is used to calculate SNR is (–17)+(+2)+(–7) or –22 dB.

Special Considerations

When two waves, traveling in opposite directions on a transmission line pass, they create a standing wave. An improperly terminated line will have a standing wave due to the signal being transmitted out and the reflected wave coming back. The effect of this phenomenon can be detrimental, depending on the length of the line and the relative value of the termination. At the very least, it will create a signal attenuation due to the reflection.

¼ Wavelengths

Sometimes a transmission line will have one or more load taps along its length. If the length of the tap is equivalent to a multiple of a quarter (¼) wavelength, then it must be considered when analyzing the channel performance. If the tap is terminating the line in a low impedance, this will be reflected back as a low impedance if the length is an even multiple ¼ wavelength (2, 4, 8 etc. times), which will result in no carrier getting through to the other end of the line. If the length is an odd ¼ wavelength (1, 3, 5 etc. times), the low impedance termination will be reflected back as an open circuit and carrier will pass the junction, although with some attenuation. Likewise, if the tap is terminated in a high impedance (open), the odd ¼ wavelength will reflect back as a low (shorted) impedance and the even as a high impedance. By using the

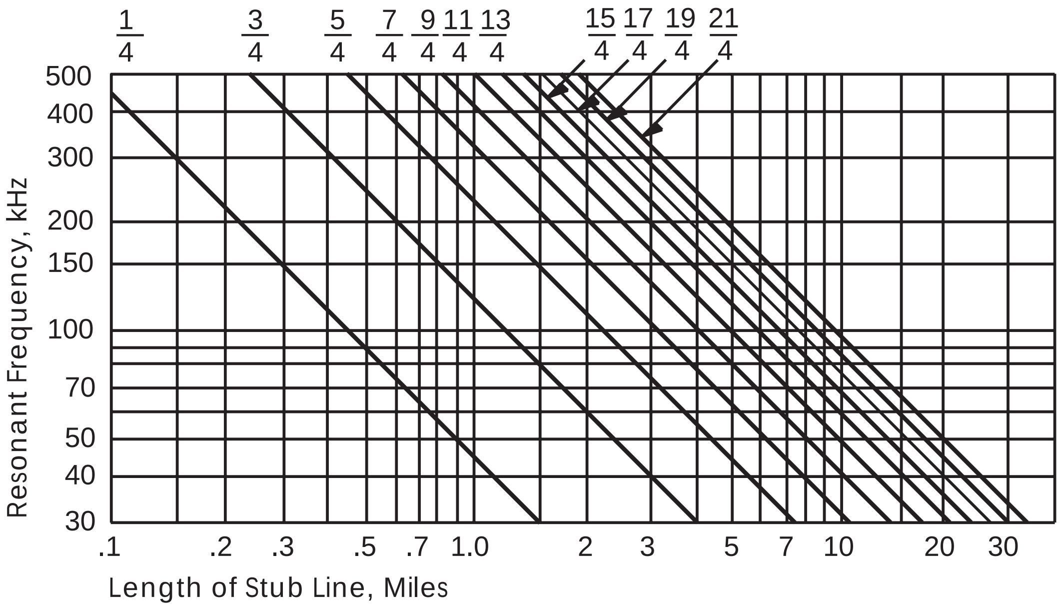

Figure 22. Resonant Frequency vs. Length in Miles to a point of Discontinuity

equation given under Power Line Characteristics, the graph in Figure 22 depicts the frequency versus length. If this is a problem, what can you do? Changing the frequency by just 1 or 2 kHz can sometimes eliminate the situation. Keeping the frequency to a multiple of odd 1/8 of a wavelength helps also. Or if these are not feasible, install a line trap at the point of the tap, on the transmission line right-of- way, not at the terminating end of the tap. This will cause the tap to be transparent to the carrier signal.

Transformer Characteristics at RF

There is no up-to-date references available on the impedances of power transformers at the carrier frequencies. The discussion below is a general discussion based on past experience, and it must be remembered that the results may be entirely different.

Generally power transformers are accepted as being a high shunt impedance at the carrier frequencies. Depending on their location in the carrier channel, their effect may or may not affect carrier channel performance. It is also commonly accepted that a power transformer connecting two transmission lines of different voltages constitutes a broad band high-frequency blocking device, preventing carrier on one line from reaching the other. Thus when a power transformer is at the terminal location of a carrier channel it will probably appear to the carrier signal as a trap.

If the transformer is terminating a load tap, what effect does it have on the carrier signal? That depends largely on the effective RF impedance to ground of the transformer and how far the transformer is from the tap point. Testing has shown that delta connected windings are more capacitive than wye-connected. This high capacitance produces a lower impedance to ground than might be expected. As discussed in the previous section, if the tap is an odd quarter wavelength long, then the impedance presented to the carrier channel is the opposite value of the terminating transformer impedance. That is, if the transformer impedance is low, then the impedance at the tap point will be high and the tap will have little effect. On the other hand, if the transformer impedance is high, then the impedance at the tap point will be low and the tap will have a significant effect on the carrier channel. In the case of taps at even quarter wavelengths, the high terminating impedance will be reflected as a high impedance with little effect on the channel and the low terminating impedance is reflected as a low impedance with a large effect.

Effects of Mismatches

Any time there is a change of impedance along the carrier signal path, there will be some reflection of the signal. This reflection is caused by the mismatching of the impedances. An example of this is when an overhead line is combined with a power cable circuit. This reflection results in a loss of the carrier signal in the transmitted direction. This loss can be calculated by the following equation:

$$ML = 20\ log\ \frac{Z_0 + Z_1}{2\sqrt{Z_0 Z_1}},$$

where ML is mismatch loss.

As an example, let's say an overhead line of 250 ohms is combined with a cable circuit of 25 ohms. This will result in an additional 4.8 dB loss.

If this mismatch point is far enough away from the transmitter to attenuate the effect of the reflection, the only loss is that calculated above. But if the mismatch point is close enough to the transmitter terminal then its effect will be more detrimental than just the mismatch loss calculated in the equation and should be investigated further. The reflected energy will cause the terminating impedance to change from the nominal characteristic impedance of the line. In fact, depending on the distance to the mismatch, the terminating impedance presented to the line tuner can be very inductive or capacitive with a low value of resistance in the termination impedance. This type of a mismatch termination will cause a significant loss of power since much of the transmitter power will be feeding the inductive or capacitive load and line tuning equipment is not designed to tune out these effects.

Modal Analysis

Prediction of carrier performance can be accomplished through the use of Modal Analysis. Modal Analysis is a mathematical tool similar to symmetrical components used for analyzing unbalanced faults on three phase power systems. Like symmetrical components, modal analysis is a practical means whose modes can be electrically generated and measured separately. Modal theory is based on the premise that there are as many independent modes of propagation on a multiconductor line as there are conductors involved in the propagation of energy. What follows is a simplified explanation of Modal Analysis.

There are five characteristics of natural modes:

1. The phase-conductor currents or voltages can be resolved into three sets of natural-mode components at any point on a lossy, reflection-free three-phase line.
2. At any point on a line, the mode components will add to the actual phase quantities, as well the total power derived be equal to the sum of the mode powers.
3. The mode characteristic impedance, which is the ratio of mode voltage to mode current, is constant on each phase conductor.
4. Each mode propagates with a specific attenuation, wave length and velocity.
5. One set of mode components can not be resolved into other mode components. There is no inter-mode coupling on a uniform line since the modes are independent.

Each mode has it own characteristics. Mode 1 is the least attenuated and least frequency dependent of the three and makes carrier channels possible on long EHV lines. The energy is propagated on the two outer phases and returns on the center phase. Mode 2 is propagated on one outside phase and returns on the other outside phase. It is more frequency dependent and has more attenuation than mode 1. Mode 3 is the highest attenuated mode and is propagated on all three phases and returns via the ground. The attenuation is so high that beyond 10 miles, mode 3 is negligible. Figure 23 shows the mode propagation characteristics.

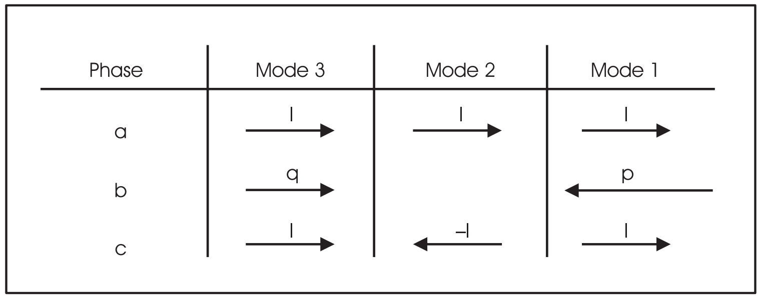

Figure 23. Mode Distribution for a Three-Phase Line

This explanation of Modal Analysis applies to a horizontally spaced, single-circuit three-phase EHV line with two overhead static wires, grounded at each tower. The static wires do not generate any transmission modes if grounded at each tower.

In Modal Analysis, you must mind your p's and q's. Coefficients p and q are center phase mode coefficients for modes 1 and 3, respectively. The values for p and q are calculated from the original matrix calculations [4][5].

The values for p and q will vary with the line under study but range from 1.1 to 1.3 for q and -1.6 to -1.9 for p. Table VIII shows data from field test on a 40 mile 500 kV line. Other field data from 345 to 765 kV lines showing the attenuation and Phase velocity for the modes is in Table IX.

Table VIII – Results of Modal Analysis

Phase	Mode 3	Mode 2	Mode 1
a	1.0	1.0	1.0
b	1.206 (q)	0	-1.66 (p)
c	1.0	-1.0	1.0
Mode Impedance (ohms)	379.00	274.00	232.0

Calculations from modal analysis can become very complex but for explanation purposes a few assumptions can be made to simplify the process. Assume the following:

- All phases and modes have the same surge impedances.
- Frequency will not be considered.
- Instantaneous currents (phase or modal) will be either in phase or 180 out of phase.

Table IX - Mode Attenuation and Phase Velocity

Mode	Attenuation (dB/mi.)		Phase Velocity, relative to Mode 1
	30 kHz	300 kHz	
1	0.01–0.03	0.07–0.09	1.0
2	0.09–0.1	0.4–0.5	0.98–0.995
3	1.5 to 3.0 at 100 kHz		0.9

With these assumptions, the basic model is as shown in Figure 24, with p = -2 and q = 1. From these developed equations, the propagation of energy on the power line can be analyzed at any point in the path. This is done by taking the phase currents (I_a, I_b & I_c) and converting them to modal quantities (X, Y & Z) then calculating the effects of the path on the modal quantities and re-converting to phase quantities. The most useful locations in the system for using these equations are at the line terminals to determine coupling efficiency and the affects of transpositions in the line.

Since mode 1 is the lowest loss mode, it is important to know how much mode 1 is generated by a particular type of coupling scheme. Mode 1 coupling efficiency is used to compare various kinds of coupling. Mode 1 coupling efficiency is an indication of the amount of mode 1 generated and compared to the total power coupled to the line. It is expressed in dB and is given by the expression

$$\eta_1 = 10 \log \left[\frac{P_1}{P_T} \right],$$

where P_1 is the power coupled into mode 1 and P_T is the total power coupled to the line. Each type of coupling can now be evaluated by substituting the current(s) as coupled, i.e. for center phase to ground coupling $I_a = I_c = 0$ and $I_b = I$. Figure 25 show the results of the mode components for the various types of coupling conditions at the transmitter terminal. The optimum coupling arrangement would produce the largest mode 1 component in the power line at the transmitting point.

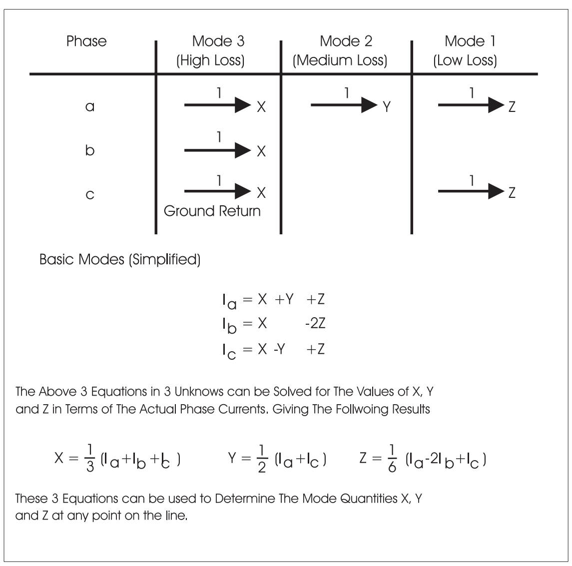

Figure 24.
Simplified Presentation of Basic Modes

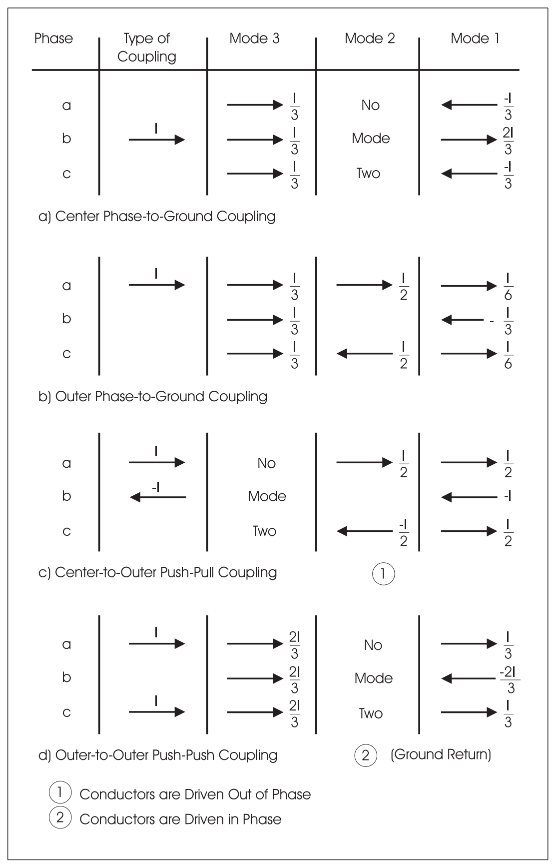

Figure 25. Mode Components for Various Types of Coupling

Table X shows different coupling arrangement efficiencies normalized to mode 1. In order of least losses, the carrier coupling can be ranked as follows:

- Mode 1 Coupling (Out on two outer phases, in on the center phase)
- Center phase to outer phase (push-pull)
- Center phase to ground
- Outer phase to outer phase with ground return (push-push)
- Outer phase to ground (only on short lines)

Table X - Mode 1 Coupling Efficiencies

Coupled Phases (unused phases grounded)	Calculated Mode 1 Coupling Efficiency (dB)	Measured Efficiency (dB)
Center-to-outer	–1.1	–1.6
Center–to–gnd.	–1.6	–2.5
Outer–to–Outer (push–push)	–2.66	—
Outer–to–Gnd.	–5.8	–7.3

On important, long EHV lines, mode 1 coupling has been justified, even though it requires line traps, coupling capacitors and line tuners in all three phases.

Transpositions act as mode converters in that it takes what is probably all mode 1 and converts the transmission to include mode 2 and mode 3 at the transposition. This can result in as much as 6 dB of a loss. This can be visualized in Figure 26. Assuming the line is sufficiently long enough for only mode 1 to be present at the transposition, the result from the transposition is that mode 2 and mode 3 are now introduced back into the circuit. Multiple transpositions result in multiple mode conversions. Most lines are not long enough to attenuate mode 2 and mode 3 before the multiple transpositions therefore these will typically result in an additional 2 dB of loss or a total of 8 dB. Three closely spaced transpositions in fact will have no loss attributable to it since the conductors essentially return to their original positions.

Modal analysis is a very complicated process to accurately determine the performance of the power line carrier coupling. While not typically done for every power line carrier application, it is presented here to provide the engineer with the understanding of why and how to best design the coupling scheme from an engineering sense as well as an economic sense.

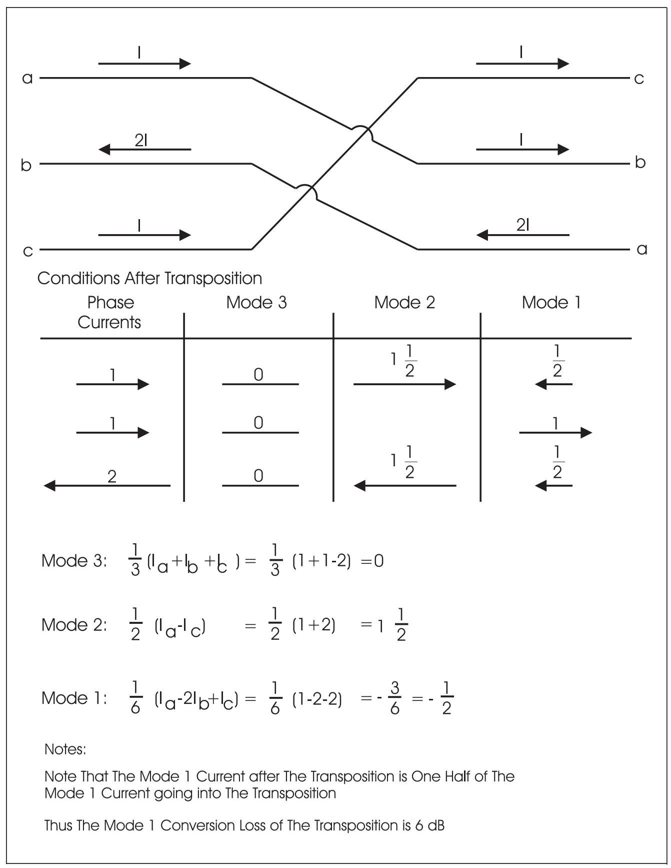

Figure 26. Mode 1 Transposition Loss

Table XI - Frequency Spacing Requirements in kHz
for AM to AM & AM to FSK Equipment

Equipment and Bandwidth	AM (on-off)			
	600 Hz w/o voice	600 Hz with voice	1200 Hz w/o voice	1200 Hz with voice
AM (on-off)				
600 Hz w/o voice	2*			
600 Hz with voice	8	8		
1200 Hz w/o voice	5	8	5	
1200 Hz with voice	8	8	8	8
FSK				
300 Hz	2*	8	5	8
600 Hz	2.5*	8	5	8
1200 Hz	4.5	8	5	8

** Spacing requirement increase 25% for each 25 kHz above 90 kHz*

Designing the System

Frequency Selections

The typical frequencies used in Power Line Carrier range from 30 to 500 kHz. In considering which frequency to use for the specific application, several things must first be considered.

1. Application requirements
   - What are the bandwidth/frequency spacing requirements?
   - Is there interference from other sources?
2. Surrounding frequencies in use
3. Frequency Planning
4. Coupling Method
5. Line configuration for noise and attenuation considerations
6. Overhead and/or power cable

The type of channel equipment and bandwidth being used will dictate the minimum frequency separation requirements. Table XI gives typical values for AM sets to AM & FSK sets and Table XII has typical values for FSK transmitters to transmitters (uni-directional) and transmitters to receivers (bi-directional). These

Table XII – Frequency Spacing Requirements in kHz for FSK Equipment

Equipment and Bandwidth	Frequency Shift Keyed		
	300 Hz	600 Hz	1200 Hz
Uni-directional (TX to TX)			
300 Hz	0.5		
600 Hz	1.5	1.5	
1200 Hz	3	3	3
Bi-directional (TX to RX)			
300 Hz	1.5	3	4.5
600 Hz	3	3	4.5
1200 Hz	4.5	4.5	4.5

tables reflect the minimum requirements, assuming a 15 dB isolation is provided with an external device between the equipment. The discussion following on paralleling equipment will go into more details as to why this isolation is required.

While this information is for signals on the same line, care must be taken to avoid interference from sources on adjacent lines or other substations. A common guideline is to separate same-frequency channels by two or three line sections. This will generally provide an approximate 45 dB cross-station attenuation. Parallel lines which will result in signal coupling should also avoid using the same frequency.

A survey of surrounding frequencies in use within two line sections of the new installation is required. If there are any lines paralleled or crossing, those frequencies should also be noted. Don't forget others who use the same frequency spectrum, such as LORAN-C and the railroad industry. The UTC maintains a database of all power line carrier frequencies in the United States. This database may be used to help coordinate frequencies with other utilities.

Establishing a plan of how to assign PLC frequencies will eliminate re-evaluating the existing system with each new installation. The plan should be consistent with achieving the maximum frequency density possible and should be evaluated periodically for its effectiveness.

The most frequently used coupling method is the single phase to ground, which uses a single frequency tuner on a single phase of the power line. This may not always be feasible if the frequencies available are not close together. Other methods may be required if the remaining frequency spectrum dictates it. Alternatives may include using double-frequency tuners, or coupling single-phase to ground on more than one phase. The advantages as well as the disadvantages must be carefully considered. Is it more justifiable to re-allocate frequencies and retune existing equipment or to acquire double frequency tuners and accept higher attenuation with outer-phase coupling? Wider bandwidth response will be required from the coupling capacitor and line trap as well, which translate into higher costs.

When selecting a frequency, the response of the line must be considered. Noise on the power line decreases as the frequency increases. But attenuation increases as frequency increases so a frequency will need to be selected that takes both of these factors into consideration. Also power cable circuits should be looked at closely for frequency selection. Cable circuits tend to have very high attenuation and the low impedance on the cable predicate a narrower bandwidth from the tuners and traps. Therefore frequencies below 70 kHz are typically used on cable circuits.

Paralleling Transmitters & Receivers

Depending on the requirements of the protection, one or more carrier transmitters and receivers may be required. It will usually be necessary to parallel these transmitters and receivers with each other in order that only one coaxial cable be run to the switchyard. There are several approaches to paralleling PLC equipment, and the approach used will depend on the type of equipment, the number of channels, and the frequencies of these channels.

Before considering the equipment needed to parallel carrier sets, let us consider the reasons why we need to be concerned with this part of the application. The requirement may be to parallel transmitter and transmitter, transmitter and receiver, receiver and receiver, or various combinations of the above.

First, consider paralleling two or more receivers. This usually does not present a problem since most receivers have input filters with high input impedance in the pass band to isolate channels from one another, and all received signals are about the same level. Therefore, it is accepted practice to directly parallel receivers at the input terminals of the equipment. One factor that may prevent the direct paralleling of receivers is if the receivers being used are designed to terminate the line. In this case, hybrids or matching transformers will have to be used to parallel the receivers so that the line is not terminated

multiple times. It is best that the receivers used have a high input impedance in their pass band so that they may be paralleled directly. Then if it is required to terminate the coaxial cable a non-inductive resistor may be placed in parallel with the receiver combination.

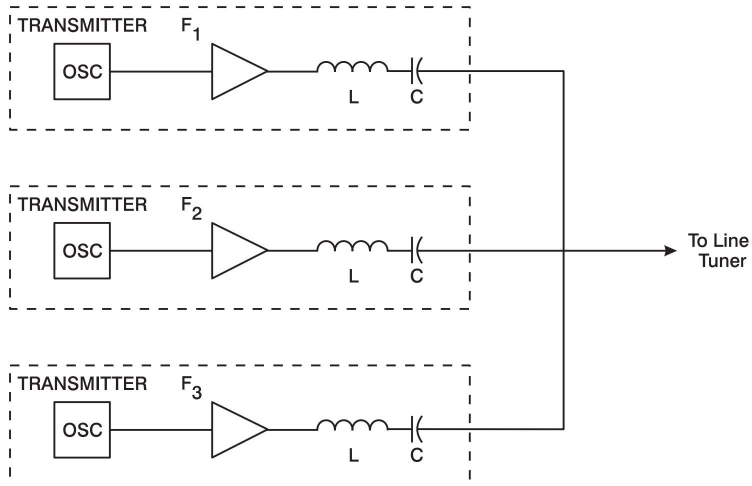

Figure 27. Paralleling of Transmitters with Internal LC Units

Second, consider paralleling two or more transmitters, When two or more transmitters are paralleled then the results may be considerably different than paralleling receivers. The output of the transmitters are high levels which cause problems when the energy from one transmitter flows into the output stages of another transmitter. If a large signal flows into the output amplifier stage of a transmitter it will cause the amplifier to operate in a nonlinear region which will result in mixing of the two primary frequencies and their harmonics. The result of this mixing process is called intermodulation distortion (IM). Many unwanted frequencies are generated which can interfere with other carrier channels on the same line or other lines. Therefore, it is an absolute must that transmitters be paralleled using some type of isolating equipment. This equipment may take the form of hybrids, simple LC units, band-pass filters, or high/low-pass filters.

Some transmitters have simple series LC units after their output stage tuned to the transmitted frequency. The LC unit will attenuate any energy attempting to enter from another transmitter thus preventing IM products from being generated. The magnitude of the attenuation depends on the frequency spacing of the two transmitters. If the spacing is large, thus attenuating the unwanted signal enough to prevent IM, then the transmitters may be paralleled directly as shown in Figure 27. The spacing required depends on the LC unit and transmitter being applied, and the actual spacing must be obtained from the manufacturer's specifications. Figure 28 shows the use of an external series LC unit to isolate transmitters which do not have the unit built internally. The principles are, of course, the same. If one wants to space the transmitters closer than an LC unit will allow then a more complex band-pass filter may be used. A band-pass filter will provide a faster roll-off for out-of-band frequencies than a simple LC filter. However, it may be desired to space the carrier frequencies even closer than a band pass filter will allow. In this case, hybrids must be used to isolate the PLC transmitters. Hybrids will be discussed below.

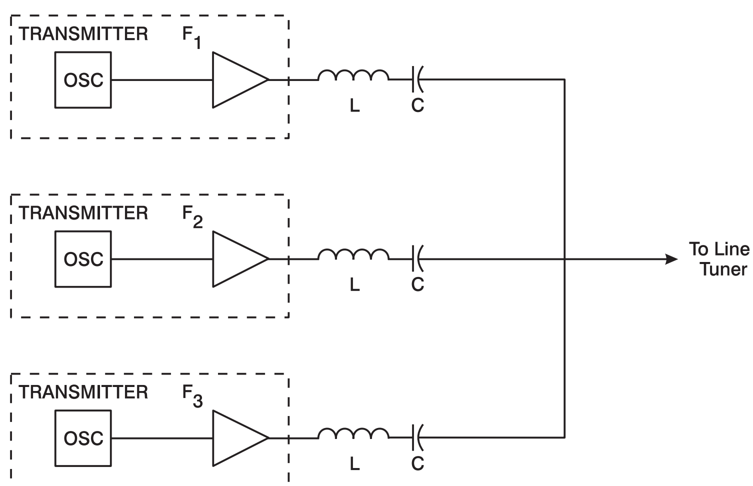

Figure 28. Paralleling of Transmitters with External LC Units

Third, consider the paralleling of transmitters and receivers. This will be required in most applications. The receiver cannot harm the transmitter if the receiver input impedance is high. However, the transmitter energy can interfere with the operation of the receiver. The receiver isolates itself from unwanted signals by the use of a sharp roll-off band-pass filter in the receiving circuits. The amount of interference a transmitter will cause to a receiver depends on frequency spacing, roll-off characteristics of the receiver filter, the transmitter power, and the type of modulation the channel is using. Figure 29 attempts to illustrate the problem of the high level transmitted signal adjacent to the receiver. The example in Figure 29 shows a local transmitter signal at +40 dBm 3 kHz from the center of the paralleled receiver. After that transmitter frequency is past through the receive filter it is attenuated by 40 dB, thus the receiver will see an interfering frequency of 0 dBm. Note that the desired receive guard is at a level of +10 dBm. If the receiver is set for a 15 dB fade margin, the receiver cannot detect a loss of channel if the guard is lost. In fact since the interfering frequency is on the trip side of the receive filter a trip may occur when the guard is lost. Thus the receiver needs more isolation than the filter can provide. Also keep in mind that this interfering energy coming into the receiver takes away from the amount of noise the receiver can tolerate from the transmission line and still make a correct decision. Therefore, it is desirable not to rely solely on the receiver filter for all the required isolation, especially in long line applications. The added isolation is usually obtained by the use of hybrids.

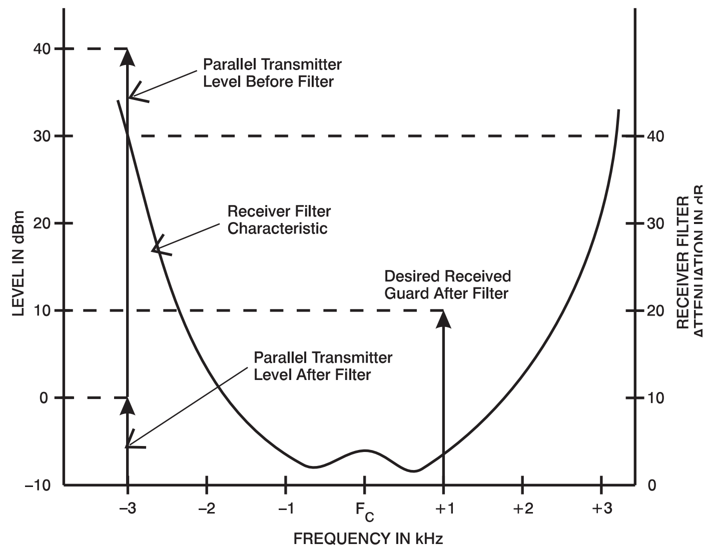

Figure 29. Interference between Transmitters & Receivers

Several typical applications of hybrids are shown in Figure 30 through Figure 34. A summary of some of the more important application rules are given below:

- All hybrids in a chain should be resistive type hybrids except the last hybrid, that is, the one connected to the line tuner.
- The last hybrid in the chain should be a reactance type hybrid or a skewed type hybrid.
- When applying transmitters to reactance type hybrids the frequency spacing between the widest spaced transmitters is about 4% for frequencies below 50 kHz and 6% for frequencies above 50 kHz. If this rule is not followed then the hybrid cannot be adjusted to provide the best possible isolation between all transmitters.

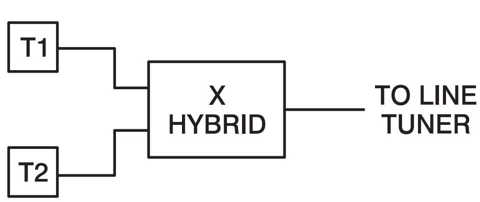

Figure 30. Hybrid Connections – Two Transmitters

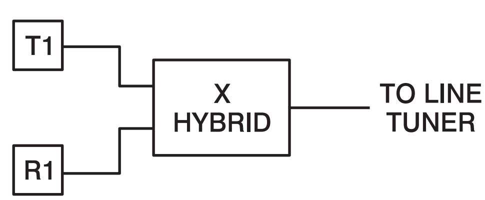

Figure 31. Hybrid Connections – Single Bi-directional Channel

- When applying transmitters and receivers to a reactance type hybrid the frequency spacing between the transmitter group and receiver group is of no concern; however, all the transmitter frequencies must meet the frequency spacing rule above. This rule is based on receivers with a high input impedance.
- When the last hybrid is a skewed type then the receiver port should be terminated with a 50 ohm resistor to obtain proper isolation.

Figure 35 shows two curves for paralleling transmitters. For any frequency spacing above the curved line, the transmitters may be paralleled directly. For any frequency spacing below the straight line the spacing is close enough to use hybrids with a reactance hybrid at the end of the chain. The shaded area of is "no man's land." Neither direct paralleling nor reactance hybrids can be used. Frequencies spaced in this area will require special treatment such as band-pass filters or high/low-pass filters. Another solution to the problem of the shaded area is to use a resistive hybrid at the end of the chain. Doing so will limit the isolation obtained if the line tuner does not terminate the hybrid in a 50 Ω resistive load.

One will find that when a system is being designed there is more than one way to put the hybrid chain together. The question, of course, is which approach is best. A few guidelines are listed below in order of importance:

- The hybrids should be arranged with the lesser losses in the transmitter path and the greater losses in the receiver path to provide more transmitter signal levels onto the power line.
- Transmitters which are used with wide bandwidth channels should be arranged with lower losses, and those of narrower bandwidths should have the higher losses. Narrow band systems are not as susceptible to noise as wider band systems are, therefore they can tolerate the higher loss.

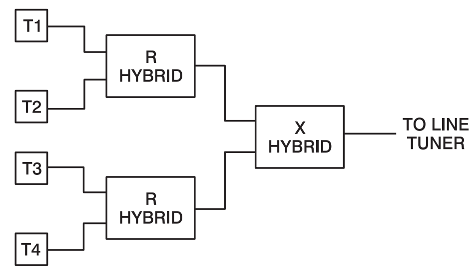

Figure 32. Hybrid Connections–
Four Transmitters(Equal Losses)

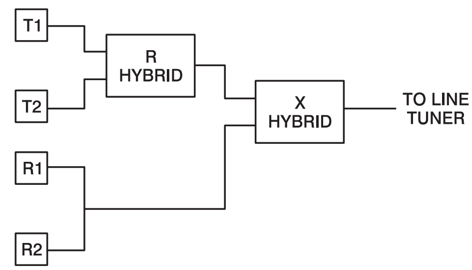

Figure 33. Hybrid Connections –
Dual Bi-Directional Channel

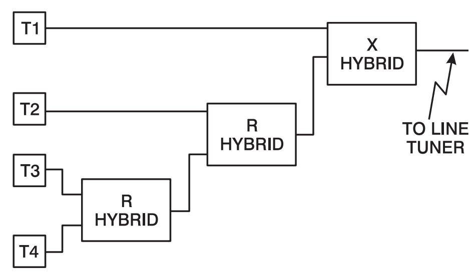

Figure 34. Hybrid Connections–
Four Transmitters(Unequal Losses)

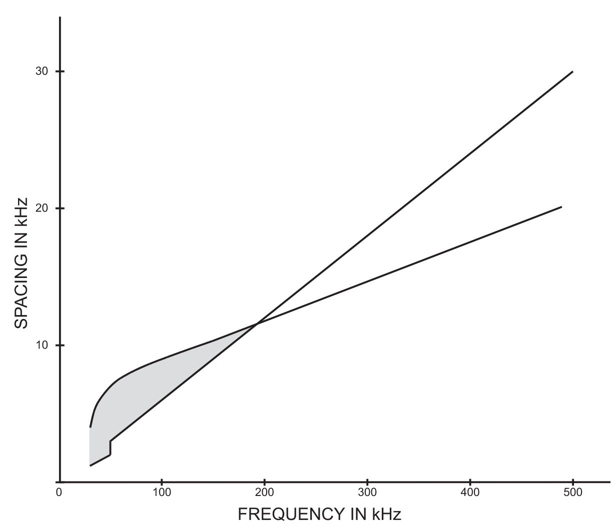

Figure 35. Guide to Connecting Transmitters
with LC Units

- If possible transmitters used for common applications should be arranged for equal attenuation. This would apply to systems which use dual channels such as Direct Transfer Trip (DTT) or Segregated Phase Comparison.

Coupling Schemes

As with most systems, there is more than one way to couple the carrier to the power line. The deciding factor may be economic, performance or a compromise of the two. That is, the best performance may be expensive to justify for the line being protected so the next best one may be the preference. Most protective relay channels use single-phase-to-ground coupling, requiring only one set of coupling equipment (line tuner, coupling capacitor and line trap). Multi-phase coupling may be used to improve dependability, but requires multi-sets of coupling equipment As stated before, the coupling schemes with least losses (ranked in order of least losses) are shown below:

- Mode 1 Coupling (Out on two outer phases, in on the center phase)
- Center phase to outer phase (push-pull)
- Center phase to ground
- Outer phase to outer phase with ground return (push-push)
- Outer phase to ground (only on short lines)

On important, long EHV lines, mode 1 coupling has been justified, even though it requires line traps, coupling capacitors and line tuners in all three phases.

What follows is a brief description of the more typical forms of coupling.

Single Line to Ground

The best single-phase-to-ground scheme uses the center phase for coupling. The center phase provides the most mode 1 coupling. Using one of the outside phases will introduce more mode 2 and mode 3 coupling than desired. Figure 36 shows an example of phase-to-ground coupling.

Phase to Phase

Some applications will require more dependability. When the protected line is of significant importance and the type of protection requires receipt of the signal during an internal fault, multiphase coupling improves dependability of the signal being transmitted through the fault. Since the most frequent type of power system fault is a phase to ground, you can improve your

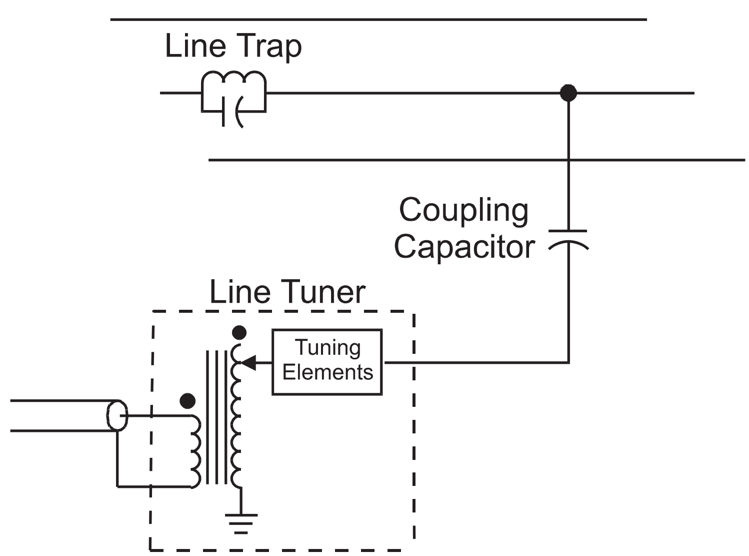

Figure 36. Single Phase-to-Ground (Center Phase) Coupling

chances of receiving the signal through the fault if more that one phase is used. Figure 37 shows how to couple using the push, pull type coupling described under the Modal Analysis section.

Mode 1

In EHV applications where the protected line is long and of major importance, mode 1 coupling is used to get the maximum received signal. As shown in Figure 38, this requires the use of three sets of coupling equipment as well as additional balancing transformers.

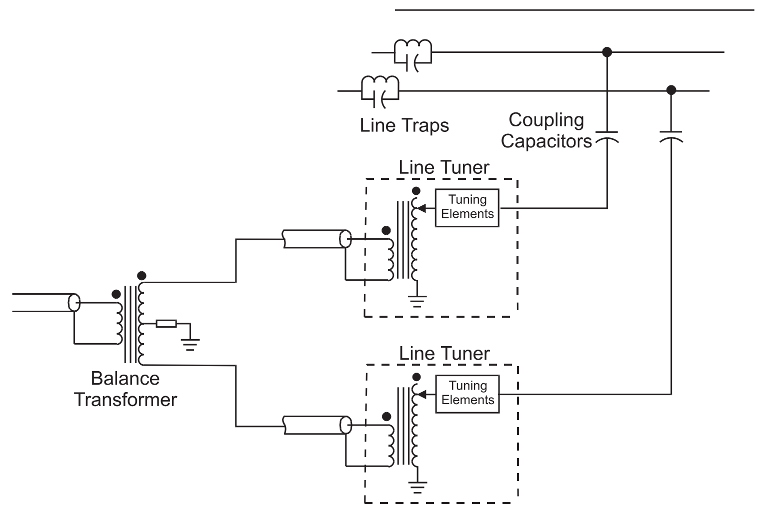

Figure 37. Phase-to-Phase Coupling

Example of Channel Performance Calculations

When calculating the channel performance, the signal at the receiver terminals, and the SNR at the receiving terminal coupling capacitor are determined. The received signal level is calculated for fair-weather conditions and then a fade margin is added in order to determine receiver sensitivity requirements. The SNR is calculated for foul-weather conditions so it may be determined if the channel has adequate transmitter power to perform properly. A typical carrier application is shown in Figure 39. Let’s begin the channel performance calculations.

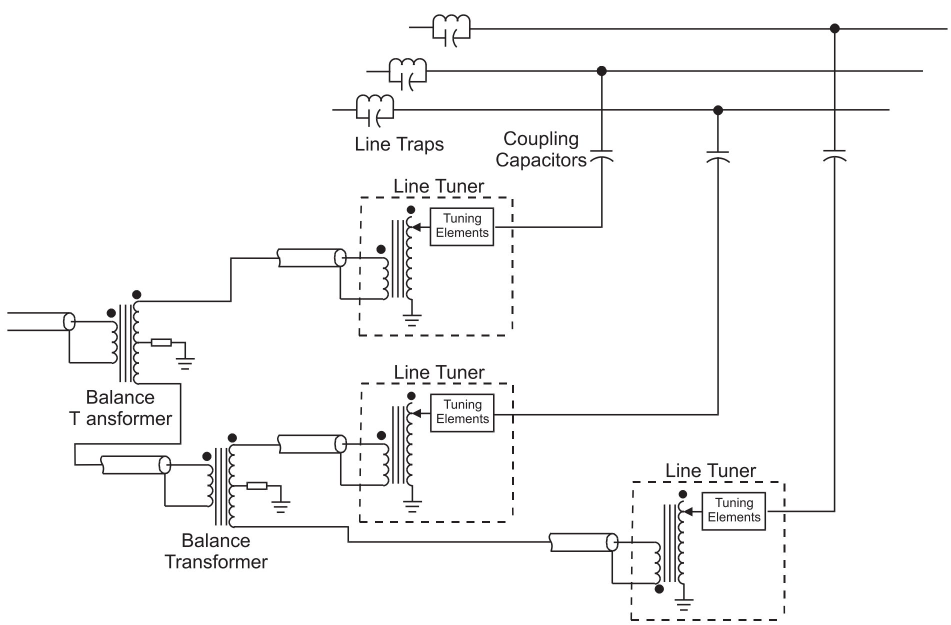

Figure 38. Mode 1 Coupling

Conditions:

- Line: 100 mile, 345 kV line with one transposition at the center. Shield wire- ACSR cable.
- Carrier Frequencies: grouped near 100 kHz
- Line Relaying: application requires wide-band frequency shift type channel with a 600 Hz bandwidth using a 1 W/10 W transmitter.
- Breaker Failure Relaying: application requires narrow-band frequency shift type channel with a 300 Hz bandwidth and a 1 W/10 W transmitter.
- R-F Hybrids: Used as shown in Figure 39. Assume the 6% rule is met. The hybrid arrangement is one of three possible.
- Line Tuner: Single-frequency tuner coupled center-phase-to- ground. The frequencies are close enough to pass through the tuner tuned to 102 kHz.
- Line Trap: Single-frequency type with the low-Q connection, tuned to 102 kHz to cover the 100-105 kHz band of signals.

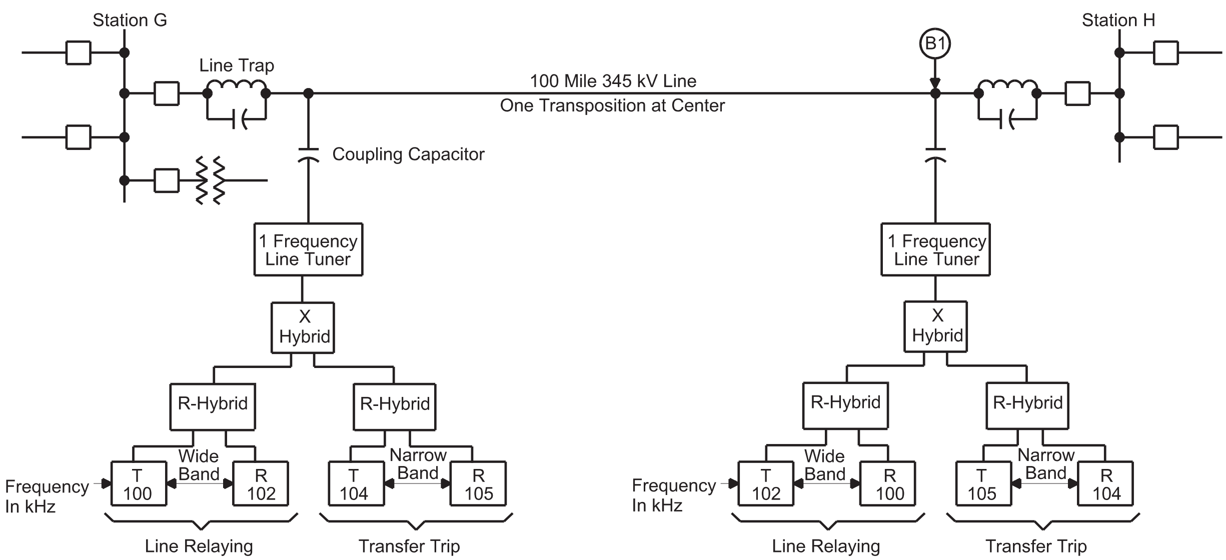

Figure 39. Example Carrier Channel for Example Calculations

Channel Loss calculation starting at station G:

- Hybrid loss: Each transmitter must pass through two hybrids. The losses are 2 X 3.5 dB = 7 dB loss.
- Coupling loss: This will include coaxial cable run, line tuner, coupling capacitor, and drain coil losses. To make an accurate calculation the manufacturer's specifications must be referred to, however, a value of 3 dB will usually cover most situations.
- Trap Shunt loss: A wide band trap will have 400 to 500 ohms blocking impedance and the line will be 350 to 450 ohms. The current division for this impedance ratio will cause about a 3 dB loss in power to the bus. Generally 3 dB will be used in all cases since it is the worst case. If the trap has higher impedance with respect to the line then the losses will be less.

- Coupling correction: Obtain from Table IV. For this system the correction is +3 dB.
- Line Attenuation: Refer to Figure 18. For a 345 kV line at 100 kHz the attenuation is 0.07 dB/mi. The total fair- weather attenuation will be 0.07 X 100 mi. = 7 dB. The foul- weather attenuation from Table II is 7 dB X 1.25= 8.75 dB. This number can be rounded to 9 dB.
- Transposition Loss: Per Table III this will be 6 dB.

Summary of system losses from station G to point B1(Figure 39):

- ➢ Hybrid loss = 7 dB
- ➢ Coupling loss = 3 dB
- ➢ Shunt loss = 3 dB
- ➢ Coupling correction = 3 dB
- ➢ Line loss = 9 dB (foul-weather)
- ➢ Transposition loss = 6 dB
- ➢ TOTAL LOSS to B1 = 31 dB

Foul-Weather Line Noise:

Calculations for 600 Hz bandwidth receiver:

- From Figure 21, at 100 kHz, foul weather noise level at 230 kV =-17 dBm
- From Table VI the correction for a 345 kV line =+2 dB
- The total 3 kHz noise level =-15 dBm
- Correction for a receiver bandwidth of 600 Hz = -7 dB(Table VII)
- Wide-band receiver noise level = -15 dBm +(-7 dB)= -22 dBm

Calculations for 300 Hz bandwidth receiver:

- From Figure 21, at 100 kHz, foul weather noise level at 230 kV =-17 dBm
- From Table VI the correction for a 345 kV line =+2 dB
- The total 3 kHz noise level =-15 dBm
- Correction for a receiver bandwidth of 300 Hz = -10 dB(Table VII)
- Narrow-band receiver noise level = -15 dBm +(-10 dB)= -25 dBm

Received SNR:

- ➢ Transmitted level(1 Watt) = +30 dBm
- ➢ Attenuation to point B1 = -31 dB
- ➢ Received signal at B1 = -1 dBm

Signal-to-noise at B1:

Calculations for 600 Hz bandwidth receiver:

- ➢ Wide-band receiver =-1dBm (signal level)-(-22 dBm) (noise level)
- ➢ SNR = 21 dB

Calculations for 300 Hz bandwidth receiver:

- ➢ Narrow-band receiver = -1 dBm-(-25 dBm)
- ➢ SNR =24 dB

The signal-to-noise ratio of both channels is well above the worst case of 10 dB allowed for a frequency shift type channel, and they are also well above the 15 dB recommended minimum. Refer to Table XIII. Note, the SNR is calculated to the point B1 (Figure 38) since it is expected that from this point on the signal and noise are attenuated by the same amount and the SNR will remain the same.

Table XIII - Recommended Signal-to-Noise Ratios for Different Carrier Systems

Function	Modulation	SNR (dB)*	In-Band SNR (dB)
Relaying			
Line Protection	ASK (On–Off)	15–20	20**
Line Protection	FSK	3–10	13
Transfer Trip:			
Slow Speed	FSK	0–5	13
Medium Speed	FSK	3–7	13
High Speed	FSK	5–10	13
Voice	SSB	25–30	25–30
	AM	25–30	25–30

**Based on Noise in a 3 kHz Bandwidth*

***Noise Level should be below receiver Sensitivity*

To determine the total channel attenuation to the carrier receivers at station H, the coupling and hybrid losses from B1 to station H must be added to the fair-weather losses to B1.

Total Channel Loss:

- ➢ Attenuation to B1 =29 dB(fair-weather)
- ➢ Coupling loss =3 dB
- ➢ Trap shunt loss =3 dB
- ➢ Hybrid loss(2 hybrids) =7 dB
- ➢ Total loss to receivers =42 dB(fair-weather)

The total losses are plotted in a level diagram of Figure 40. The signal level at the receivers are +30 dBm-42 dB = -12 dBm signal power. Since it is common practice to adjust the receivers for a 15 dB margin, the receiver sensitivity should be set at -27 dBm. The alarm setting should probably be set to -22 dBm. It must be checked to see if the receiver being used has the capability of being set to a level of -27 dBm. If so, then this carrier example will provide a reliable communications link.

Typical Relaying Schemes using Power Line Carrier

Protective Relaying schemes use pilot channels to transmit local information to the remote end in order to make the proper decision to trip or not to trip for a fault on the line. These types of scheme or systems can be classified according to the type of modulation the channel uses.

A blocking system is one where the channel is used to indicate an external fault, sending a signal to prevent tripping (or block). This is a very dependable relay system since the channel is not required in order for the relays to trip the line. These types of systems typically utilize an “on-off” type carrier, where the carrier is normally in its OFF state until it needs to send a blocking signal.

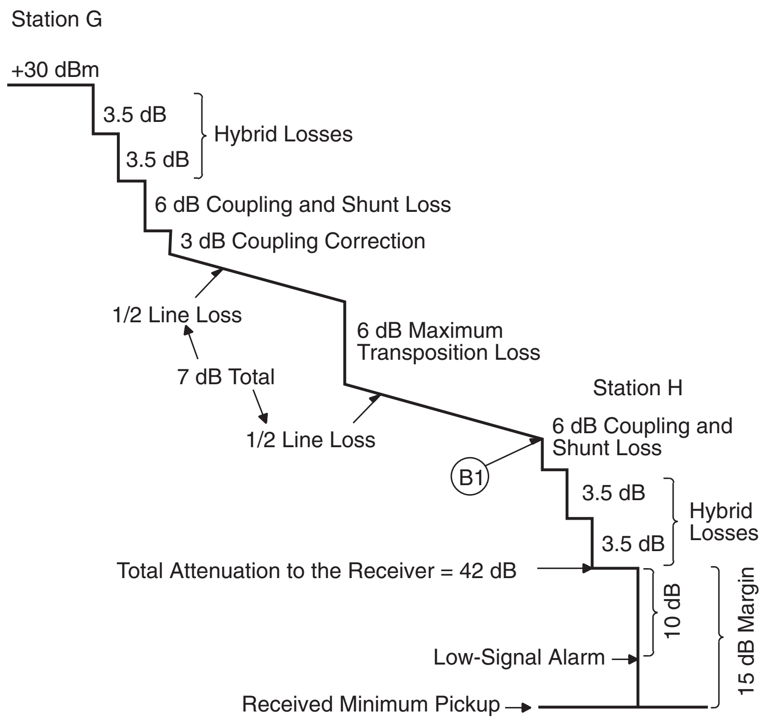

Figure 40. Carrier Loss Diagram for Example in Figure 39.

A permissive overreaching transfer trip system uses the channel to indicate an internal fault, allowing the system to trip (i.e. giving permission). This is a very secure system since the relays cannot falsely operate without a signal present from the remote end. These types of systems utilize the frequency-shift keying carrier, transmitting a guard signal under normal conditions, shifting to a trip frequency when keyed by the relay to initiate a trip. However, in the case of the Power Line Carrier Channel, the signal will have to be transmitted over the faulted line. Depending on the phase(s) involved, the fault may attenuate the signal, preventing the receipt of the remote information. To compensate for this, there is an “unblock” window in the receiver logic which allows tripping on loss of channel for some predetermined time, usually on the order of 150 ms. The addition of this 150 ms window provides the system with the dependability of a blocking system, while also being secure as in a permissive system.

Consideration for Choosing The Right Channel Modulation

Individual philosophy and past experience tends to dictate the type of channel chosen for relaying purposes. One of the foremost reason is the availability of the channel. Since Power Line Carrier is over the power line itself, the channel is already present. It tends to be one of the most economical channels available for relaying and the relay engineer has full control of the communication channel. The next step is which type of modulation to choose. Philosophy tends to play a larger influence in this area. With an On-Off channel, the channel is not required for tripping, only for blocking for an external fault. With proper application and tuning of the coupling equipment, an external fault will not significantly affect the carrier signal. One draw back is that the channel is not continuously monitored. But with the addition of an automatic checkback system, some of this is mitigated. Frequency shift channels are continuously monitored but require that the signal be transmitted across the same power line where the fault has occurred. The Unblock system compensates for this shortcoming.

Directional Comparison

Directional Comparison relaying interprets the direction of the power flow during a power system fault. If the fault power is detected to be flowing inward at both ends, the fault is internal. An external fault is when the fault power flow is inward at one end and outward at the other end. It is desirable for the relay system to trip for an internal fault and block for an external fault.

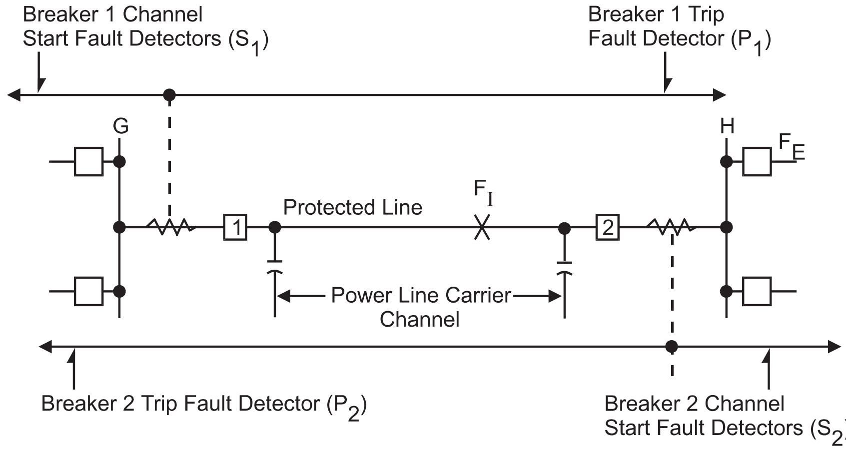

Figure 41. Blocking Scheme

Blocking

The basic elements for directional-comparison blocking systems are shown in Figure 41 and Figure 42. At each terminal, the phase and ground trip units (P) must be directional and set to overreach the remote terminal; that is, they must be set to operate for all internal faults. Nominal settings of the distance units are 120 to 150 percent of the line. The start units (S) must reach farther, or be set more sensitively, than the remote trip units. Thus S1 must be set more sensitively than P2 or reach farther behind bus G. Likewise, S2 must be set more sensitively than P1 or reach farther behind bus H. In any case, the S and P relays should be similar in type. If the trip unit (P) is a directional overcurrent ground relay, the start (S) ground relay should

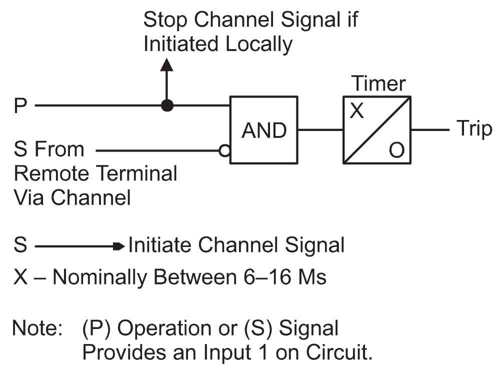

Figure 42. Basic Blocking System Logic

Table XIV– Operation of the Directional Comparison Blocking Schemes.

EXTERNAL AND INTERNAL FAULTS		
Type of Fault	**Events at Station G**	**Events at Station H**
External (F_E) For external faults, the CS unit or timer x/o assure that a blocking signal is established.	P_1 operates; S_1 does not see fault. Blocking signal received from station H. RR back contacts open (or 1 signal negates AND). No trip.	S_2 operates to key transmitter. Blocking signal sent to station G. P_2 does not see fault. No trip.
Internal (F_I)	P_1 operates; S_1 may or may not operate, but P_1 operation prevents transmission of a blocking signal. Breaker 1 tripped.	P_2 operates, S_2 may or may not operate but P_2 operation prevents transmission of a blocking signal. Breaker 2 tripped.

** For external faults, the CS unit or timer x/o assure that a blocking signal is established.*

be a similar non-directional overcurrent unit. The same principle applies for the phase relays.

When the on-off power line carrier is used with these schemes, except for possible auxiliary functions, no signal is normally transmitted, since the S units operate only during fault conditions.

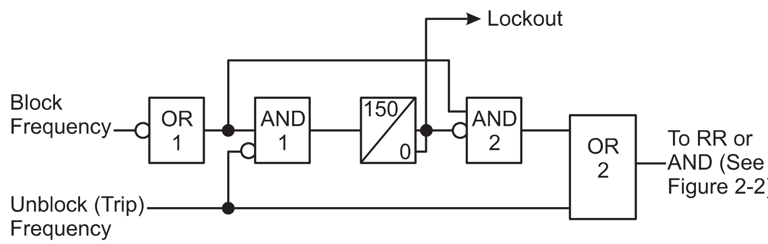

Figure 43. Basic Unblock Receiver Logic

Operation of the directional comparison blocking scheme shown in Figures 41 and 42 is given in Table XIV for both external and internal faults. Subscript 1 indicates relays at station G for breaker 1; subscript 2, relays at station H for breaker 2.

The blocking scheme is still widely used for its flexibility and reliability. Since the communication channel is not required for tripping, internal faults that might short and interrupt the channel are not a problem. Over tripping will occur, however, if the channel fails or is not established for external faults within the reach of the trip fault detectors. Since the carrier transmitter is normally OFF, or non-transmitting, channel failure cannot be detected until the system is tested or until an external fault occurs. This limitation can be overcome by using a checkback system with the carrier.

Because the carrier is "ON/OFF" modulated, only one frequency (f_C) is required for line protection. When applied to three terminal lines, phase cancellation may occur when two or more transmitters are keyed simultaneously. To prevent this, you should offset transmitters by ±100 Hz. The three frequencies should be:

- f_C
- f_C – 100 Hz
- f_C + 100 Hz

Unblocking

The Directional-Comparison Unblocking systems transmit a continuous blocking signal, except during internal faults. The channel is generally a frequency-shift keyed (FSK) power line carrier. For an internal fault, the FSK transmitter is shifted to the "unblock" frequency. The transmitted power in many applications is normally 1 W, boosted to 10 W during unblock operation.

The frequency-shift channel is monitored continuously to prevent tripping when a loss of channel occurs. The carrier receiver logic is

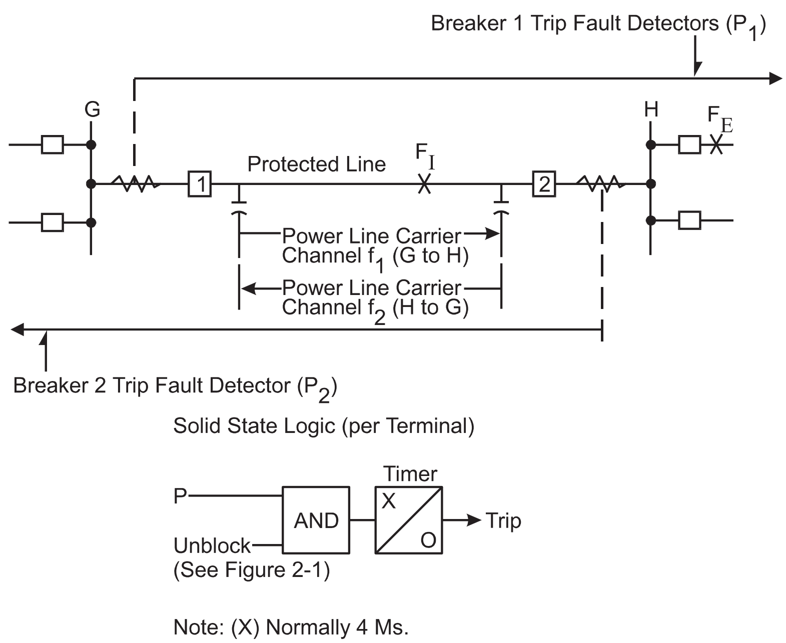

Figure 44. Basic Unblock System

Table XV– Operation of the Directional-Comparison Unblocking.

EXTERNAL AND INTERNAL FAULTS		
Type of Fault	**Events at Station G**	**Events at Station H**
External (F_E)	P_1 operates. f_1 channel shifts to unblock. f_2 channel continues to block. No trip.	P_2 does not see fault. Loss of block and/or receipt of unblock (f_1) operates RR or inputs AND. No trip.
Internal (F_I)	P_1 operates. f_1 channel to unblock. Loss of block and/ or receipt of unblock (f_2) operates RR or inputs AND. Trip.	P_2 operates f_2 channel shifts to unblock. Loss of block and/or receipt of unblock (f_1) operates RR or inputs AND. Trip.

shown in Figure 43. Under normal conditions, a block frequency is transmitted and OR-1 has no input. Because AND-1 and AND-2 are not satisfied, OR-2 is not energized. For an internal fault, the block frequency is removed. Assuming that the unblock signal is shorted out by the fault, OR-1 provides a direct input to AND-2 to satisfy its input requirements for 150 ms. AND-2 inputs to OR-2 to provide input to the AND shown in Figure 44. Without an unblock signal, 150 ms is allowed for tripping. After this period, lock out is initiated as one of the inputs to AND-2 is removed. This resets the RR or removes the input to AND. If the unblock signal is received, it inputs directly to OR-2 to energize the RR or to provide input to AND. The unblock signal also removes an input to AND-1 to stop the timer. A channel failure (no block or unblock signal) provides input to AND-1 and, after 150 ms, locks out the relaying and triggers an alarm. The operation of the scheme shown in Figure 44 is given in Table XV for external and internal faults. The phase and ground trip fault detectors at both stations must operate for all internal faults; that is, they must overreach the remote bus.

The scheme is most appropriate for two-terminal lines, but is applicable to multi-terminal lines. Separate channels are required between each terminal and the remote terminal(s).

You may conserve frequency spectrum by using a narrowband frequency shift carrier, but at the expense of channel speed.

Permissive Overreaching Transfer Trip Systems

Overreaching transfer trip systems require a channel signal to trip, and are used with a frequency-shift audio tone, modulated on a communication channel (e.g., public or private telephone lines). These systems are generally not used with power line carriers. There are, however, successful applications of power-line carrier on POTT schemes where parallel lines allow for cross-coupling of the carrier signal.

Permissive and Non-Permissive Underreaching Transfer Trip Systems

For overreaching systems, the directional phase and ground trip fault detectors (P) must be set to overlap within the transmission line and not overreach any terminals (see Figure 45). That is, at least one trip fault detector (P) must operate for all internal faults, and none should operate for any external fault. In practice, distance relays are normally required for both ground faults and phase faults, although directional instantaneous ground-overcurrent relays might meet these requirements in some cases.

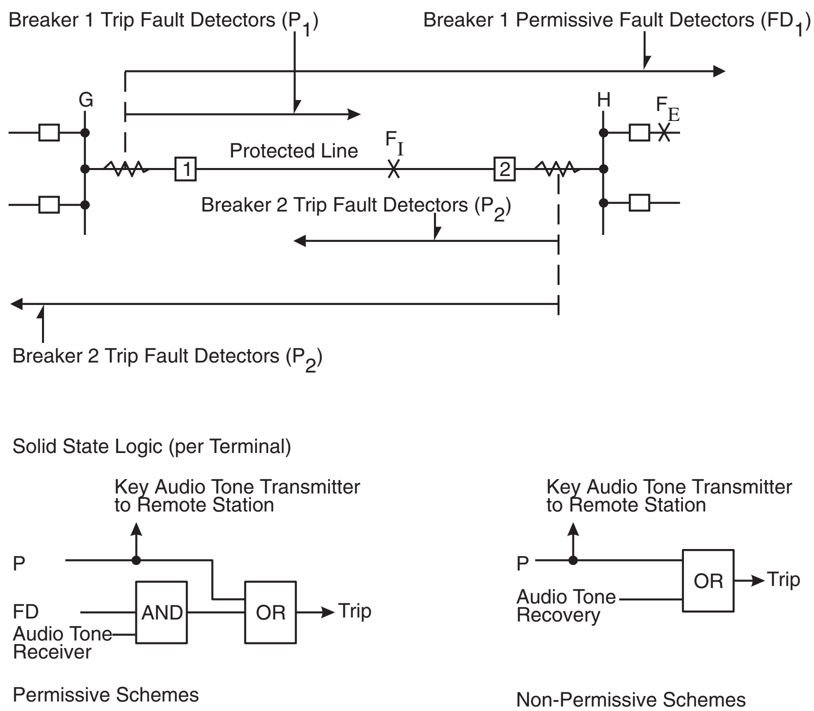

Figure 45. Basic POTT System

Table XVI. Operation of the Underreaching Transfer Trip Scheme.

EXTERNAL AND INTERNAL FAULTS		
Type of Fault	**Events at Station G**	**Events at Station H**
External (F_E)	P_1 does not operate. No channel signal sent to H. No trip.	P_2 does not operate. No channel signal sent to G. No trip.
Internal (F_I) (Fault near station H)	P_1 does not operate. No channel signal sent to H. †(FD_1 operates). Transfer-trip (f_2) from station H operates RR or inputs to AND (or OR if non-permissive). Trip.	P_2 operates and trips directly. Transfer-trip signal keyed to station G. †(FD_2 operates). Trip.

† Omitted in non-permissive systems.

Though it is the least complex, the non-permissive system is rarely used because of the high potential for false outputs from the channel, which would cause incorrect tripping. If a non-permissive system is used, the channel considerations should be as described later for direct trip systems. The system is made permissive by the additional set of phase and ground overreaching fault detectors (FD), which must operate for all internal faults (see Figure 45).

Operation of the underreaching transfer trip scheme shown in Figure 45 is described in Table XVI for external and internal faults.

Because the trip fault detectors (P) do not operate for external faults, underreaching transfer trip systems do not require external fault-clearing coordination circuits (transient blocking) and are, therefore, inherently simpler than any of the other schemes. You obtain maximum security if you use additional permissive fault detectors. These schemes also provide minimum operating times for many faults that are tripped directly, without using the channel.

Phase Comparison

Phase comparison relaying compares the phase angle of the fault currents at the two terminals of the protected line. If the two currents are essentially in-phase (in terms of primary currents), the relays detect an external fault and do not initiate a trip. If these two currents are approximately 180 degrees out-of-phase(in terms of primary currents), the relays detect it as an internal fault and initiate a trip to the appropriate breakers. To do the comparison, a secure communication channel must exist between the two ends. This channel may be over any medium desired: power-line carrier, metallic pair, leased telephone lines, microwave or fiber optics.

Phase comparison systems are typically current-only meaning 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 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 carrier are divided into three major categories, differences are related to channel equipment and sequence filter outputs:

1) Single Phase-Comparison Blocking

2) Dual phase-comparison Unblocking

3) Segregated Phase Comparison Unblocking

Blocking

Single Phase Comparison Blocking

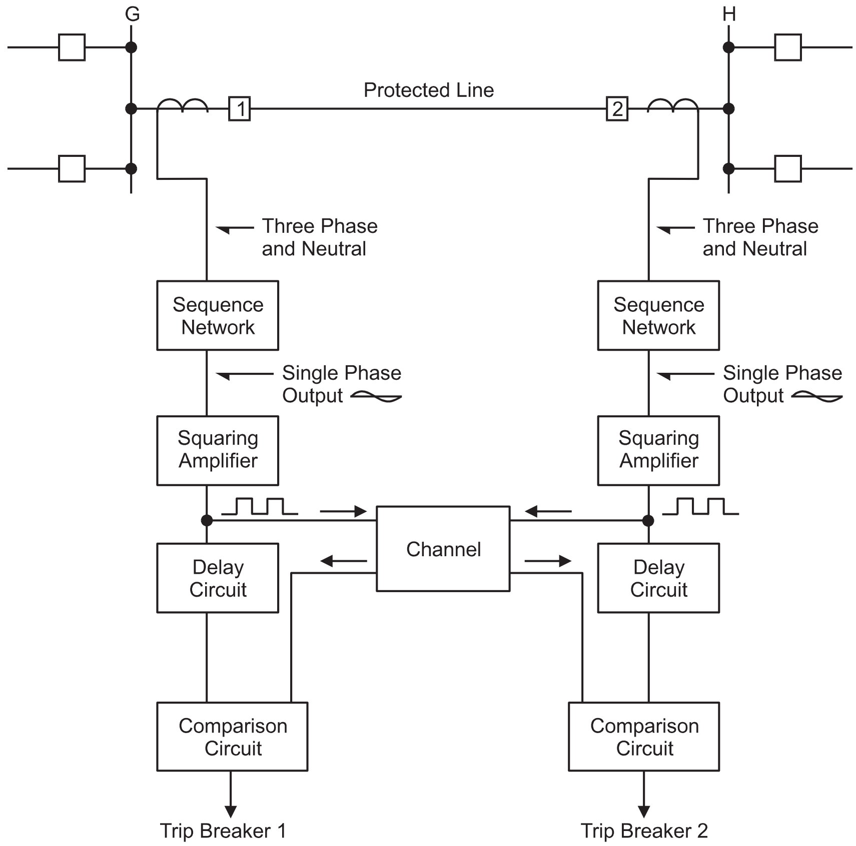

Figure 46. Basic Elements of a Phase Comparison System

Basic elements of the phase-comparison systems are shown in Figure 46. The system uses a composite sequence current network to provide a single-phase voltage output proportional to the positive, negative, and zero sequence current input. Sensitivity to different types of faults depends on the weighting factors or constants designed into the sequence current network. Adjustments to the network are provided.

A squaring amplifier in the controlling relay converts the single-phase voltage output to a square wave. The positive voltage portion corresponds to the positive half-cycle of the filter voltage wave and the zero portion corresponds to the negative half-cycle. The square wave is used to key the on-off carrier, transmitting to the remote terminal. The square wave from the remote terminal is compared to the local square wave, which has been delayed by an amount equal to the absolute channel delay time. This comparison of the local and remote square waves at each terminal determines whether a fault is internal or external.

Fault detectors are used to determine whether a fault has occurred and to supervise tripping. The fault detectors must be overreaching, i.e., set sensitively enough to operate for all internal phase and ground faults.

Because overcurrent fault detectors are normally used, voltage transformers are not required. Such a scheme is current only. Fault detectors should be set above maximum load, yet operate for all internal faults. Distance fault detectors, which require voltage transformers, are used on heavy-loaded or long lines when distance supervision is required.

Single Phase-Comparison Blocking, Current Only

In the current only system, the carrier is used with two overcurrent fault detectors (FD_1 and FD_2). FD_1, the carrier start unit, is set more sensitively than FD_2 and permits the local square wave signal to key the “ON/OFF” carrier transmitter. FD_2, set with a higher pickup than FD_1, is used to arm the system for tripping. For transmission lines less than 100 miles long, the FD_2 pickup is set at 125 percent of FD_1. For lines longer than 100 miles, the FD_2 pickup is set at 200 percent of FD_1. On a three-terminal line, FD_2 is set at 250% of FD_1, provided the line length between any two breakers is less than 100 miles. Phase-

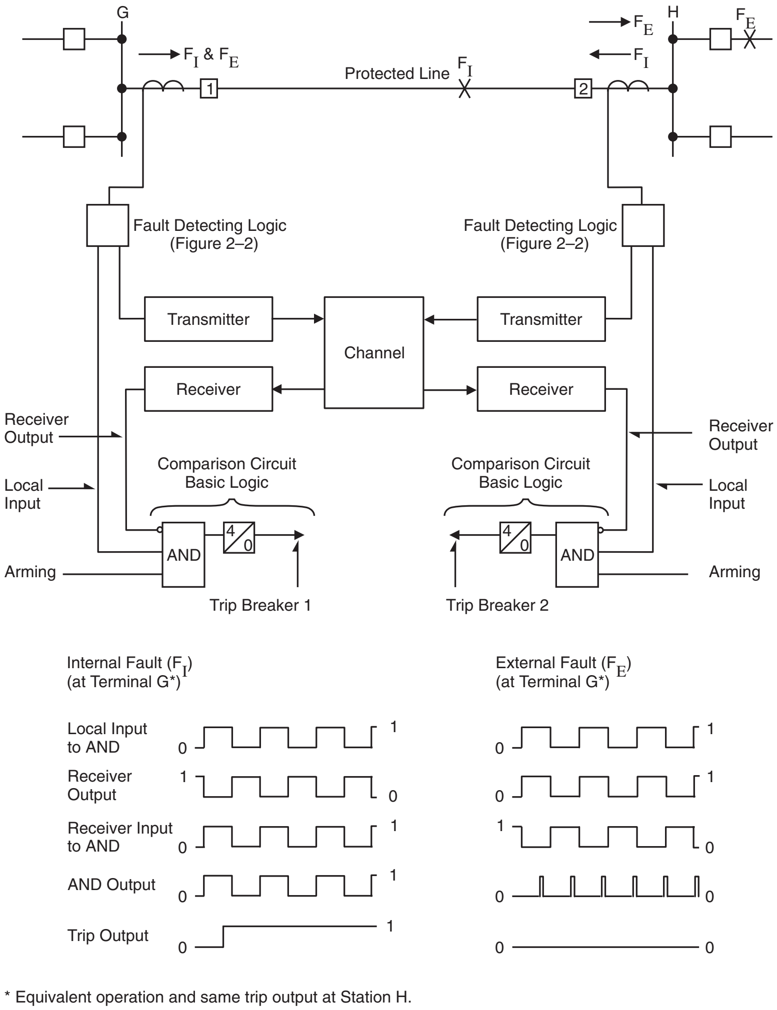

Figure 47. Phase Comparison Blocking System

Comparison cannot occur until FD_2 operates. The purpose of the two fault detectors is to coordinate the comparison of the local and remote square waves with the keying of the carrier square wave. The carrier must be started before the comparison is allowed to ensure that the remote square wave has been received.

The basic operation of the system is shown in Figure 47. FD_1 and FD_2 at both terminals operate for an internal fault (F_I). The square wave inputs to the AND from the local currents are essentially in phase with those transmitted via the channel from the remote terminal. The local square wave turns the carrier "ON" and "OFF" to provide the square wave receiver output for the remote terminal.

A flip flop is energized if the inputs to the AND continue for 4 ms, providing a continuous trip output supervised by FD_2 operation. The 4 ms correspond to a phase angle difference of 90°, on a 60 Hz base, between the currents at the two terminals. The currents at the two ends of the line may be out of phase by up to 90° and still trip. This is a blocking system, since the receipt of a signal from the channel prevents tripping. The carrier signal, therefore, does not have to be transmitted through the internal fault. No received signal puts a "1" on the AND input. With the remote terminals open, this system provides sensitive instantaneous overcurrent protection for the entire line. As is characteristic of blocking systems, the channel is not required for tripping on internal faults.

For an external fault, such as F_E in Figure 47, blocking is essentially continuous, since the remote wave input to the AND is out-of-phase with the local square wave. The secondary CT currents are essentially out-of-phase for an external fault. The currents can, however, be in-phase by up to 90° on a 60-Hz base and still block.

Single-Phase, Distance-Supervised Comparison Blocking

A distance-supervised scheme should be used if the minimum internal three-phase fault current is less than twice the maximum load current. Twice maximum load current allows FD_1 to operate positively on the minimum internal three-phase fault, yet reset when an external fault is followed by a maximum load current flowing through the line. The on-off carrier operates in the same manner as when used with the current-only scheme, except for the fault detection and arming techniques.

Two sequence current networks and two distance relays supplement the two overcurrent fault detectors.

One sequence current network responds only to negative and zero sequence currents, detecting all phase-to-phase and ground faults (but not three-phase faults). The output of this adjustable network operates the conventional overcurrent FD_1 and FD_2 fault detectors. The two distance relays operate only for three-phase faults. Thus, FD_2 provides the arming function for all unbalanced phase and ground faults, through the adjustable filter, and one of the distance relays (21P) provides arming for all three-phase faults.

The second and non-adjustable sequence current network operates through the squaring amplifier, providing the local square wave and the carrier-keyed square wave required for phase comparison. This signal is keyed by FD_1 and the second distance relay (21S) to provide the carrier start functions. This second network responds to positive, negative, and zero sequence currents. Separate networks provide greater sensitivity: with phase-to-phase faults, for example, more than twice the sensitivity is gained.

Unblocking

Dual Phase Comparison

Dual comparison systems require a duplex channel: one frequency for each line terminal. The carrier frequency-shift channel equipment is available for this purpose; normally used in an unblocking system. Continuous channel monitoring is also provided, because either a mark or space carrier signal is always transmitted.

The transmitter is keyed to its mark frequency when the square wave from the filter goes positive, and is keyed to its space frequency when the square wave is at zero. There are two outputs at the receiver: the "mark" output is a square wave that goes positive when a mark frequency is received; the "space" output goes positive when a space frequency is received.

The basic operation of the Dual Phase-Comparison system is shown in Figure 48. For internal faults, the single phase outputs of the sequence current networks are essentially in phase, although such output represents currents 180° apart in the power system. The network output goes through a squaring amplifier that keys the frequency shift transmitter. An adjustable delay circuit delays the local square wave by a time equal to the channel delay time.

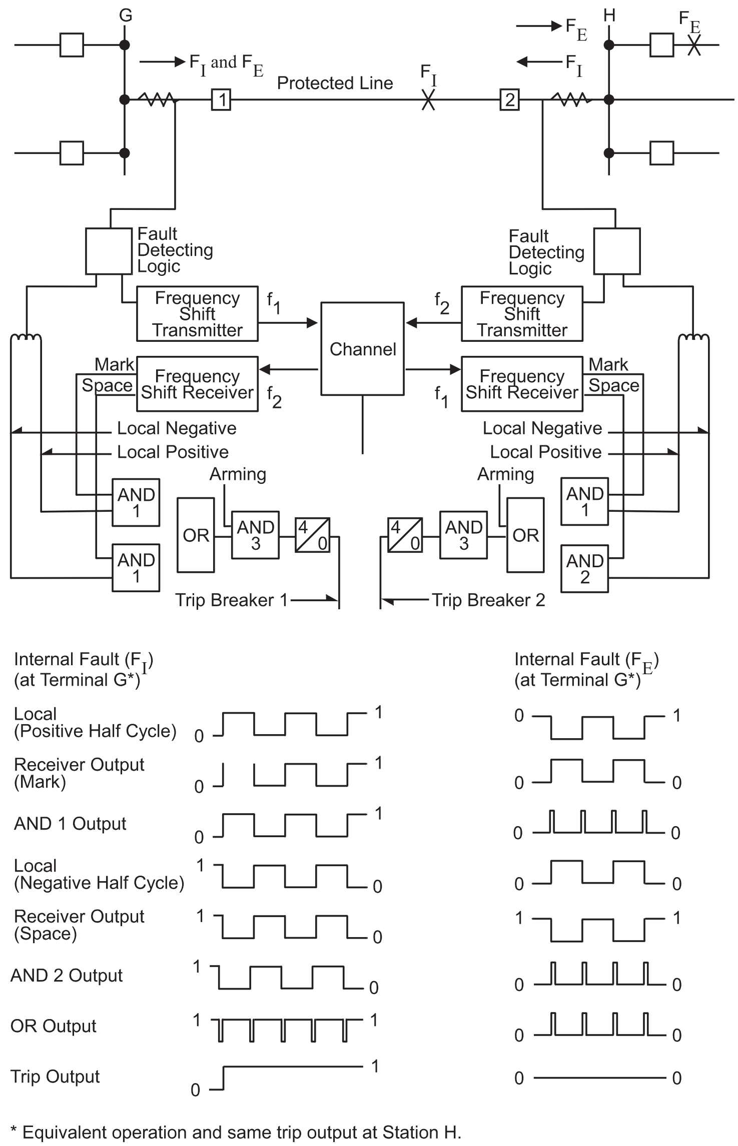

Figure 48. Basic Dual Phase Comparison System

The network output is then used to develop two complementary square waves. One wave, which has a positive state during the positive half-cycle of the sequence current network, is compared with the receiver's mark output. The other wave, which has positive output during the negative half-cycle of the sequence current network, is compared to the receiver's space output in a second comparison circuit.

On internal faults, the positive half-cycle of the local square wave lines up with the received mark output to provide an AND-1 output (see Figure 47). On the negative half-cycle, this local square wave lines up with the received space output to provide an AND-2 output. If an arming signal is received (FD_2 and/or 21P) and either AND-1 or AND-2 output exists for 4 ms, an input to the trip flip flop initiates breaker tripping. The same operation occurs at both terminals, tripping breakers 1 and 2 simultaneously on either half-cycle of fault current.

For tripping, both the mark and space frequencies must be transmitted through the internal fault via power line carrier channels. If these frequencies are not received, the receiver detects a loss of channel and clamps both the mark and space outputs to a continuous positive state. This loss of channel clamp enables both comparison circuits, allowing the system to trip on the local square wave input only. After 150 ms, the system output clamps these to the zero state. At this point, the system cannot trip and is locked out. An alarm indicates loss of channel.

For external faults, the reversal of current at one end shifts the square waves essentially 180°. As a result, neither AND-1 nor AND-2 has the sustained output required to operate the 4 ms timer (see Figure 48). No trip occurs at either line terminal.

Segregated Phase Comparison

The Segregated Phase-Comparison system has been developed to improve pilot relay protection, particularly for the long EHV series capacitor-compensated transmission lines. Long EHV series capacitor-compensated lines are a source of significant transients during the fault period. Under these circumstances, sequence current networks designed to operate at normal system frequency may present a problem. The experience with these Phase-Comparison systems has, however, been remarkably good. Directional-Comparison systems, on the other hand, are subject to mis-operation on series capacitor-compensated lines, particularly if the capacitor gaps do not short the capacitors on faults. Segregated phase comparison systems, which are current-only, are independent of the following phenomena:

- Power system frequency and wave form
- Effects of impedance unbalance between the power system phase circuits.
- Maximum load/minimum fault current margin.

The segregated phase comparison system can be divided into two types: a two-subsystem scheme and a three-subsystem scheme. In the two-subsystem scheme, one subsystem operates from delta current (I_a-I_b) for all multiphase faults, and a ground ($3I_0$) current subsystem operates for all ground faults. The three-subsystem scheme has a subsystem for each phase (I_a, I_b, and I_c).

Both segregated Phase-Comparison systems incorporate "offset keying," enabling them to trip for internal high-resistance ground faults and internal faults with outfeed at one terminal. No other system can clear these types of faults without extra logic or channels. On a 500 kV line with a 2,000:5 current transformer ratio, for example, the three-subsystem scheme will operate for ground-fault resistance up to about 100 ohms primary impedance. Under the same conditions, the two-subsystem scheme will operate up to about 200 ohms primary fault resistance.

The two-subsystem package is suitable for all applications except single-pole tripping, where the three-subsystem package must be applied. The basic operation of the scheme is illustrated in Figure 49, and each comparison subsystem operates as the dual phase comparison system described above. Each current is fed through a noninductive resistor, supplying a voltage output to the squaring amplifier (SA) that is exactly proportional to the primary currents. The output of these amplifiers is used to key the individual channels and, through the local delay timers (LDT), to provide the local square waves for comparison. The timers are adjustable between 2 and 20 ms to compensate for the delay time of the channel. This digital delay circuit translates the pulse train independently of the pulse width ratio, in contrast to the ac phase angle shift used in the other systems. The ac phase shift delay uses frequency-dependent components, which are accurate only at system frequency and can "ring" during transient conditions.

The square wave comparison is made independently for each current in the separate subsystems. Separate carrier channels are required for each of the subsystems.

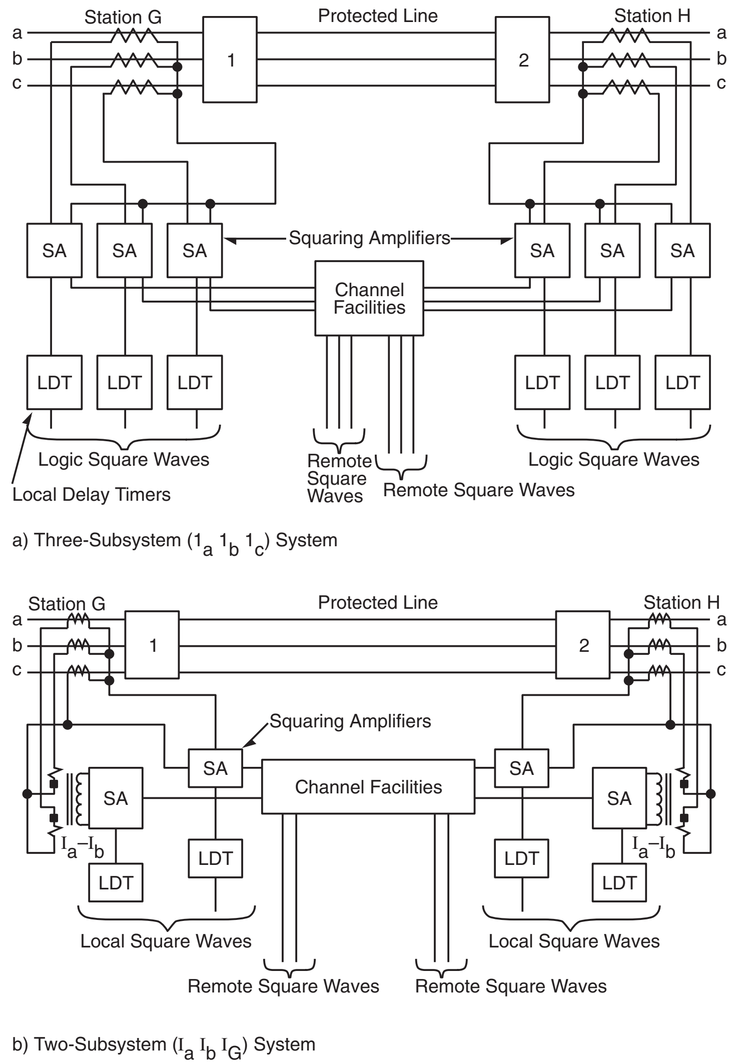

Figure 49. Basic Segregated Phase Comparison Systems

To generate the local and keying square waves, conventional phase comparison systems use thresholds equivalent to (or very near) the zero axis. As a result, an internal fault with outfeed looks like an external fault to those systems. The offset keying technique permits the relay system to trip for internal faults with outfeed current out at one terminal. While the outfeed condition is very unusual, it presents difficult problems to the great majority of pilot relaying systems when it does occur. Outfeed can occur in any of the following cases:

- Series-capacitor-compensated parallel lines.
- Weak-feed or zero-feed applications, particularly with heavy through load.
- Some multi-terminal applications.
- Series-compensated (line-end compensation) line with a source inductive reactance smaller than series capacitor reactance.
- Some single-line-to-ground faults, occurring simultaneously with an open conductor, where the fault is on one side of the open conductor.

- Some single-line-to-ground faults with high fault resistance and heavy through load (such conditions can cause outfeed only in the faulted phase current, not in the ground subsystem).

The offset keying technique allows the relay system to work like a true current differential scheme. The scheme takes advantage of the fact that, for the outfeed condition, the current into the line is greater in magnitude than the current out of the line for the internal fault.

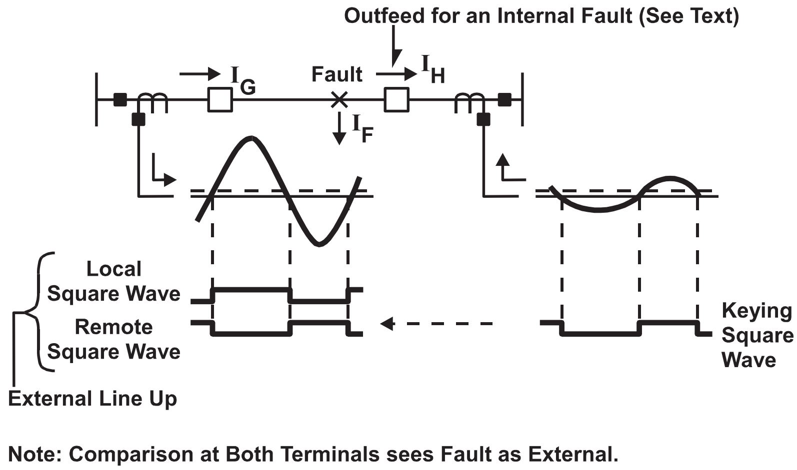

Figure 50. Outfeed for an Internal Fault

This relationship is illustrated in Figure 50, where I_G equals I_F plus I_H. While the two terminal currents may have any angular relationship with one another, most outfeed conditions display a nearly out-of-phase relationship. The out-of-phase condition illustrated is the most difficult case for phase comparison, as well as the most common outfeed condition.

In the offset keying technique, the keying threshold is displaced in the positive direction, away from the zero axis. The local square wave thresholds are displaced negatively. To maintain security, the local thresholds are separated from each other, providing "nesting" during external faults. Typical settings are shown in Figure 51.

Direct Transfer Trip

Direct transfer-trip systems provide circuit-breaker tripping at remote or receiver terminals, without any supervision by fault detectors. The most important consideration in a direct transfer-trip system is the type of channel applied. The communications equipment must carry the total burden of system security and dependability.

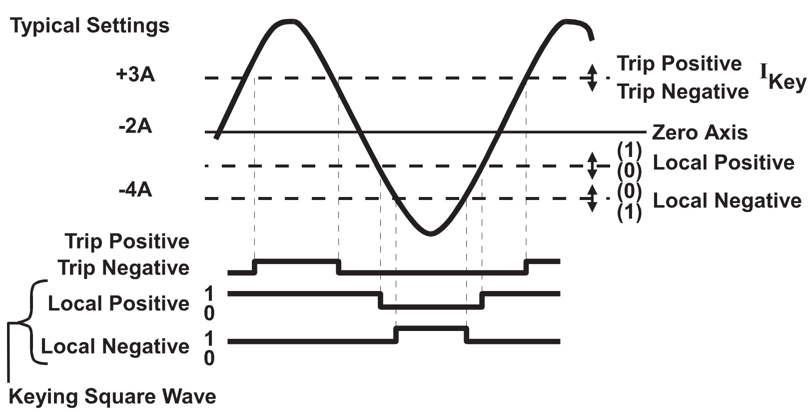

Figure 51. Off-set Keying Typical Settings

Direct transfer-trip systems are applied for:

- Line protection with non-permissive under reaching transfer-trip systems.
- Transformer protection where there is no circuit breaker between the transformer and transmission line.
- Shunt reactor protection.
- Remote breaker failure protection.

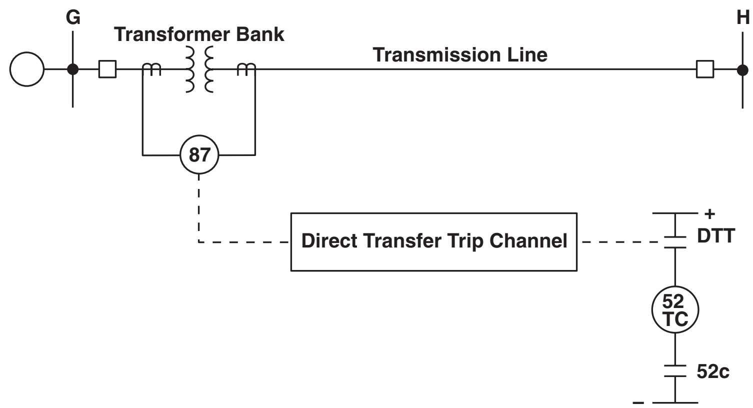

Figure 52. DTT for Transformer Protection

Transformer Protection

A typical transformer protection scheme is illustrated in Figure 52. A direct trip channel is keyed to the trip state when the transformer protective relays operate. The received trip signal will then trip the remote end breaker and lock out reclosing.

Although it is no longer widely used, you may use a ground switch operated by the transformer protective relays for transformer protection. In this technique, a ground fault is initiated on the transmission line at G, providing adequate fault current for the ground relays at H to trip the breaker at H. This system is slower but is widely used on lower voltage systems and is fairly simple and straightforward. It does not require any secure communication medium between G and H. For this type of application, the ground relays at H can be set to operate for 100 percent of the line and not overreach to bus G.

While a single switch on one phase is normally applied, you may use a double switch on two phases to initiate a double-phase-to-ground fault. In the latter case, both phase and ground relays can operate to ensure redundancy. Fault grounding is not applicable to all systems because of high short-circuit capacity.

Shunt Reactor Protection

Shunt reactors are frequently used on HV and EHV lines. These line reactors are connected on the line side of the circuit breakers (see Figure 53). A remote trip channel is thus required for a fault in the shunt reactor.

Remote Breaker-Failure Protection

A remote breaker-failure system is necessary where a multi-breaker bus, such as a breaker-and-a-half or ring bus scheme, is applied at a transmission line terminal. A direct transfer-trip system will be a part of the remote breaker-failure protection.

Direct Trip Channel Considerations

The channel and its terminal equipment are major factors in the

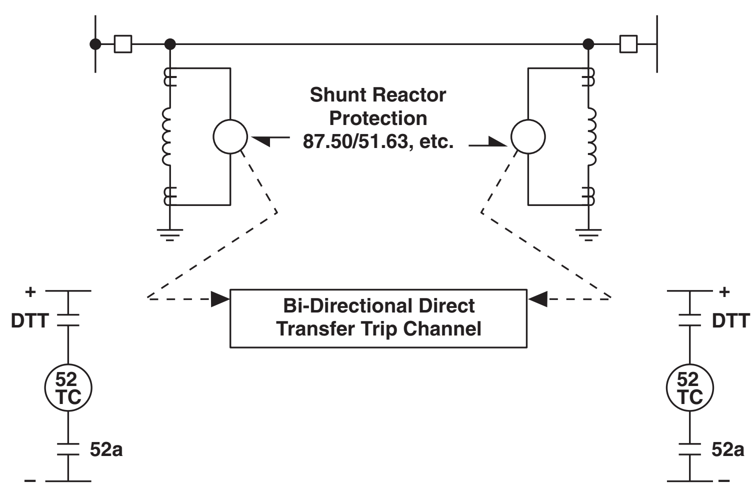

Figure 53. DTT used for Shunt Reactor Protection

proper operation of the direct transfer-trip system. The channel must neither fail to provide a correct trip signal nor provide a false signal.

While other types of modulation are possible, frequency-shift keyed (FSK) equipment offers the best compromise between noise rejection capability and equipment complexity. Two frequencies are usually transmitted in an FSK system: the "guard" frequency is transmitted during non-trip conditions and the "trip" frequency is transmitted when a breaker trip is required. Because a signal is always present, the FSK system will allow the channel to be continuously monitored. Continuous channel monitoring is necessary in a direct trip system, because breaker tripping is not supervised by any local relays.

As noise in the channel increases, a point is reached where there is a high probability of false tripping. The level of noise at which the channel becomes unreliable must be determined by tests. Signal-to-noise ratio monitors must then be included with any direct trip channel, to block possible false tripping. It is important, however, not to get the noise monitors any more sensitive than required, since their operation will prevent tripping.

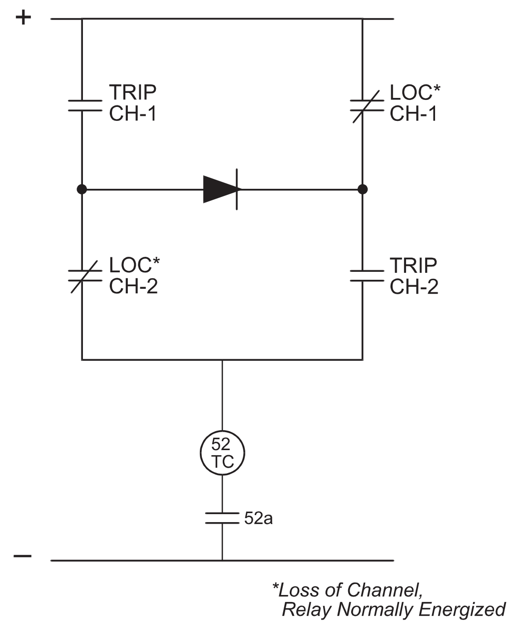

Figure 54. Revert to Single Channel DTT Scheme

There are three important aspects to the application of FSK channels to direct trip systems: channel bandwidth, dual channel systems, and channel protection.

Although faults should be cleared in the shortest possible time, speed is not the only criterion for selecting equipment. ***It is important to use the narrowest bandwidth equipment possible.*** A wide bandwidth channel may give the desired speed, but more noise enters the system. Thus, the channel will block tripping sooner than a narrower bandwidth channel with the same received signal level. A wideband channel will consequently not be as dependable as a narrower channel under equal receive-level conditions.

A dual channel system is recommended for direct trip applications. Two FSK channels should be used in series, so that both must trip before the breaker is tripped. Many tests have indicated that dual channels improve the security of the direct trip system by several orders of magnitude. Use of a dual channel system has very little effect on dependability, even if both channels are on the same transmission medium.

If you want to increase the dependability, you can modify the dual channel transfer trip scheme to allow a single channel trip when there is failure of the other channel. A typical Dual Channel Throw over to Single Channel Scheme is illustrated in Figure 54.

Three-Frequency FSK Applications

Frequency-shift carrier equipment is available in either the two- or three-frequency mode. The three basic frequencies are as follows:

f_C Center frequency

f_H High-frequency, is a frequency shift (Δf) above f_C

f_L Low-frequency, is a frequency shift (Δf) below f_C

The maximum value of Δf depends on the bandwidth of the carrier set. For a bandwidth of 1,200 Hz maximum, Δf is 500 Hz. A bandwidth of 300 Hz yields a maximum Δf of 100 Hz, while the 600 Hz bandwidth Δf can be either 250 or 100 Hz. The center channel frequency (f_C) can vary from 30 to 535 kHz.

In the two-frequency systems, only f_H and f_L are used. The two frequencies function differently and take on different labels when operating with the different types of protective relay systems. In a three-frequency system the center frequency (f_C) is the "guard" state. The lower (f_L) and higher (f_H) frequencies are "trip" states. One trip state is usually used for line protection and the other state is used for a DTT system. The DTT trip state will take precedence over the line relaying state if both are keyed concurrently.

Conclusions

The application of Power Line Carrier can be very simple or can be quite challenging, depending on the line characteristics and the desired use. What has been presented here is items that may need consideration when applying Power Line Carrier for the purpose of Transmission Line relaying to provide the relaying system with a reliable channel. While not all applications will be as challenging as those with underground cable, transformer taps or quarter-wavelength problems, it is hopeful that what is presented here can give the PLC engineer insight as to the reasons why and how the channel will perform. Although Power Line Carrier is a well-established technology and new technologies are coming into the forefront for Transmission Line Relaying, Power Line Carrier will be applied to protective relaying systems for some time to come.

References

1. IEEE Std. 643-1980, IEEE Guide for Power-Line Carrier Application
2. ABB Power T&D Co., Inc. (1982) Applied Protective Relaying.
3. Jones, D.E. and Bozoki, B. "Experimental Evaluation of Power-Line Carrier Propagation on a 500 kV Line." IEEE Transaction Paper No. 65-935. June 1963.
4. Perz, M. "Natural Modes of Power Line Carrier on Horizontal Three-Phase Lines." IEEE Transactions, Paper No. 63-936. June 1963.
5. Perz, M. "A Method of Analysis of Power Line Carrier Problems of Three-Phase Lines." IEEE Transactions, Paper No. 63-937. June 1963.
6. Tatsuo Udo, Mikio Kawai, "Fault Generated Impulse Noise Voltage in a Transmission Line," IEEE Transactions on Power Apparatus and Systems, Volume PAS-86, No. 6, PP 684-687, June 1967.
7. IEEE Std 100-1992, The New IEEE Standard Dictionary of Electrical and Electronic Terms.
8. Specht, T.R. and Cheek, R.C. "Carrier Frequency Characteristics of Power Transformers." AIEE Technical Paper No. 52-98. December 1951.
9. GET-8034, Relaying Communication Channels, General Electric Protection & Control.

Biographies

Miriam P. Sanders is the Product Manager for the Power Line Carrier products at Pulsar Technologies, Inc. in Coral Springs, FL. A graduate of University of North Carolina at Charlotte, she started her career at Westinghouse Relay Division in Coral Springs. She held several positions subsequently with ABB in Coral Springs, Raleigh, NC and Allentown, PA as well as one at Booth and Associates, Consulting Engineers. Miriam is Senior Member in IEEE and a member of the Power Systems Relaying Committee. She is presently Chairman of the Transformer Protection Guide Working Group and is Standards Coordinator for the PSRC. Miriam is registered as a Professional Engineer in Florida and North Carolina.

Mr. Roger E. Ray is the Vice President of Engineering at Pulsar Technologies, Inc. in Coral Springs, FL. Mr. Ray holds a Bachelor of Science in Electrical Engineering from Pennsylvania State University and a Masters of Engineering from New Jersey Institute of Technology. Before helping to form Pulsar Technologies, Mr. Ray was employed by Westinghouse and ABB in the area of Protective Relaying and Communications. He has received many patent awards and an IEEE Prize Paper award. He is currently Subcommittee Chairman for the Power Line Carrier subcommittee of the Power Systems Communications Committee, and is a past chairman of the PSCC.