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PRIME CONSIDERATIONS IN POWER LINE CARRIER SEPARATION SCHEME

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Abstract- Power Line Carrier (PLC) has been around longer than we 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 3feet in diameter. As technology progressed, so did the PLC equipment. There are still many PLC's 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. This paper 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.

Keywords: PLC, Hybrid Circuits, Line Tuner, Triaxial Cable.

I. INTRODUCTION

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 [1, 2].

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 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.

II. 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.

III. 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.

IV. TRANSMITTERS AND 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.

V. HYBRIDS AND 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.

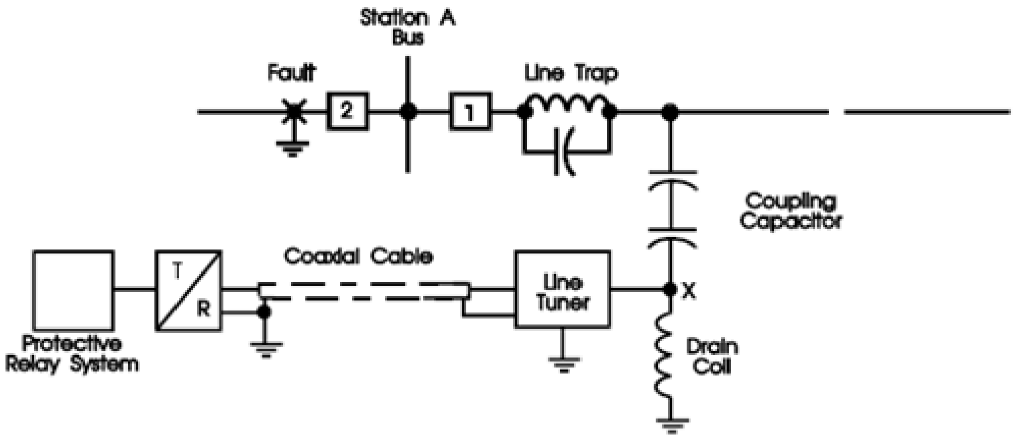

Figure1. Basic Power Line Carrier Terminal

VI. LINE TUNERS

The purpose of the line tuner in conjunction *i*th 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 low impedance at the power frequency and because of its inductance it will have 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.

VII. 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 operates 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. 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 not having to tune a LC unit.

VIII. COAXIAL CABLES AND LEAD-IN CONDUCTOR

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

A. 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 1 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.

B. 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 ha s 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.

Table 1. The attenuation versus frequency for RG-8/U cable

Frequency (kHz)	Loss (dB/1000 feet)
30	0.38
50	0.44
100	0.55
150	0.66
200	0.77
300	0.90

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 2.

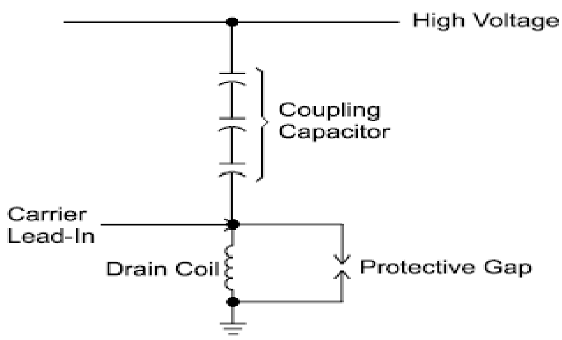

Figure 2. Coupling capacitor& drain coil combination

The single frequency tuner, shown in Figure 3, 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-frequency tuner. Figure 4 shows the frequency characteristics of the single frequency tuner.

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 5 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 5 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 are shown in Figure 4.

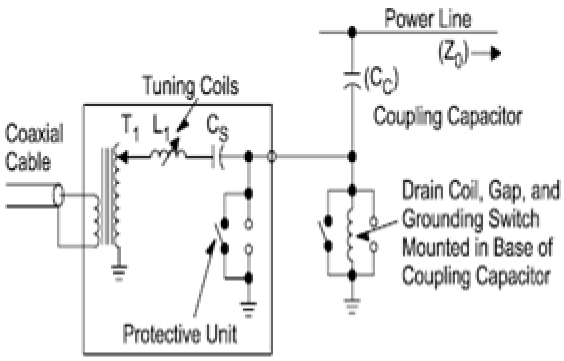

Figure 3. Single frequency line tuner

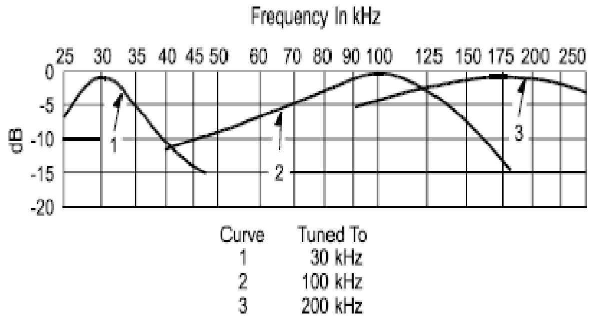

Figure 4. Single frequency tuner characteristics

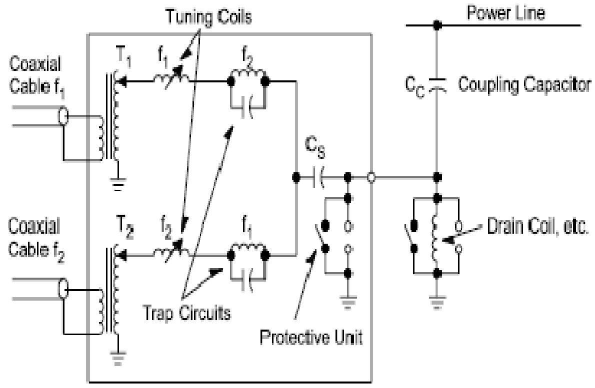

Figure 5. Double frequency line tuner

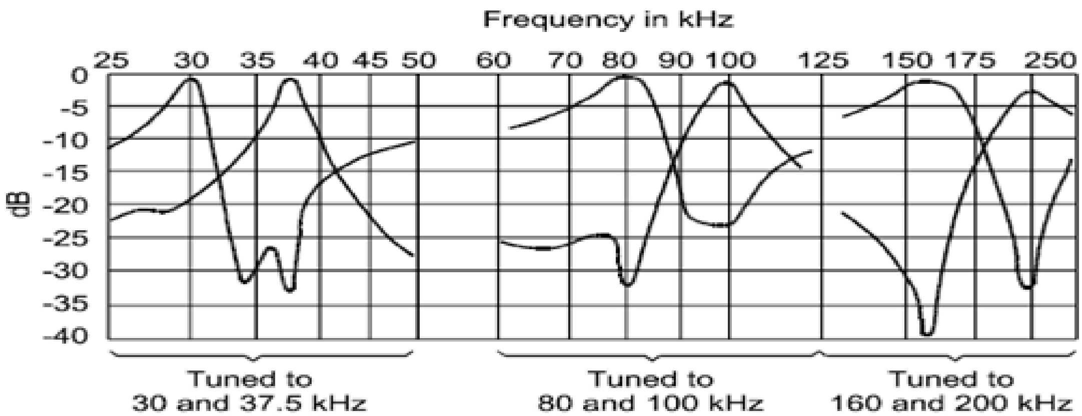

Figure 6. Typical Characteristics of Double Frequency Line Tuner

IX. 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:

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

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."

X. LINE ATTENUATION

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. 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 7 and Figure 8. As indicated in Table 2, 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.

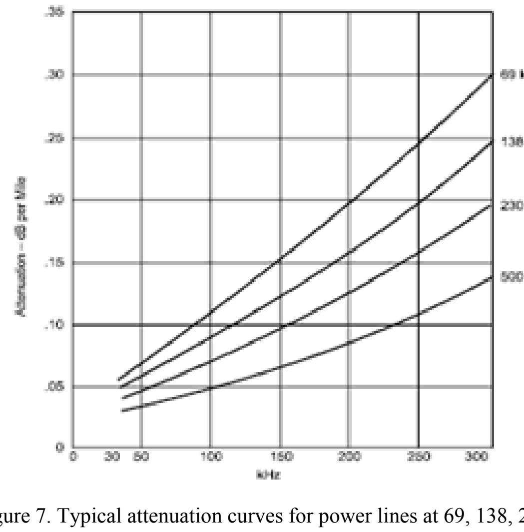

Figure 7. Typical attenuation curves for power lines at 69, 138, 230 and 500 kV

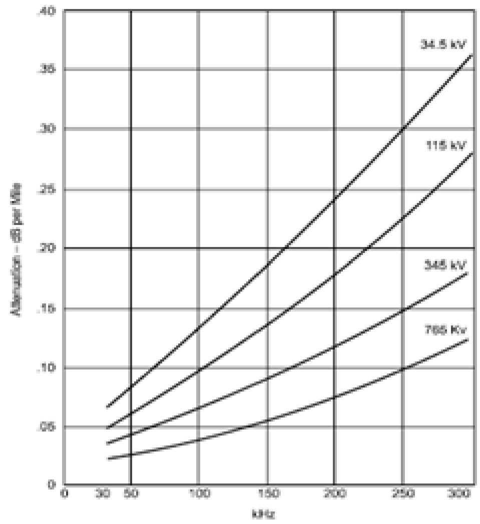

Figure 8. Typical attenuation curves for power lines at 34.5, 115, 345 and 765 kV

The corrections for transpositions in the line are shown in [3]. The type of coupling will affect the overall line loss 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 phases to ground types, that is, the carrier signal is coupled between one phase and ground.

XI. 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.

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 [5].

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. The typical fair- and foul weather average noise levels for a 230 kV line and a 3 kHz bandwidth are shown in [4].

XII. FREQUENCY SELECTION

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
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 2 gives typical values for FSK transmitters to transmitters (uni-directional) and transmitters to receivers (bi-directional).

Table 2. Frequency spacing requirements for FSK equipments

Equipment and Bandwidth	Frequency Skin 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

XIII. PARALLELING TRANSMITTERS AND 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.

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 is 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 9. 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 10 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 bandpass 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.

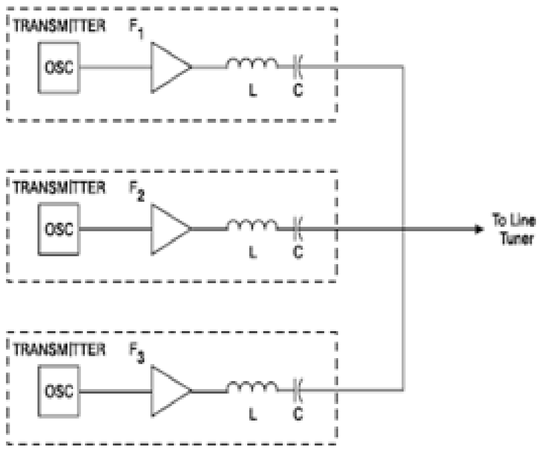

Figure 9. Paralleling of transmitters with internal LC units

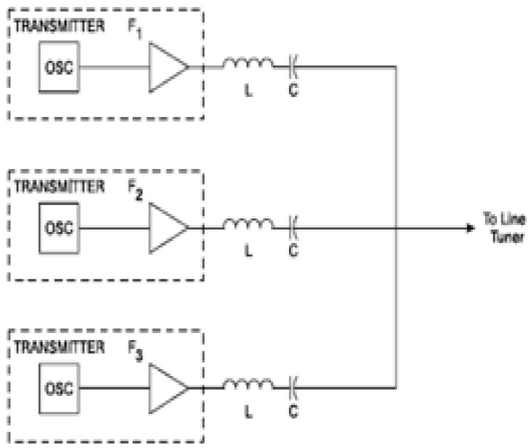

Figure 10. Paralleling of transmitters with external LC units

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 11 attempts to illustrate the problem of the high level transmitted signal adjacent to the receiver. The example in Figure 11 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.

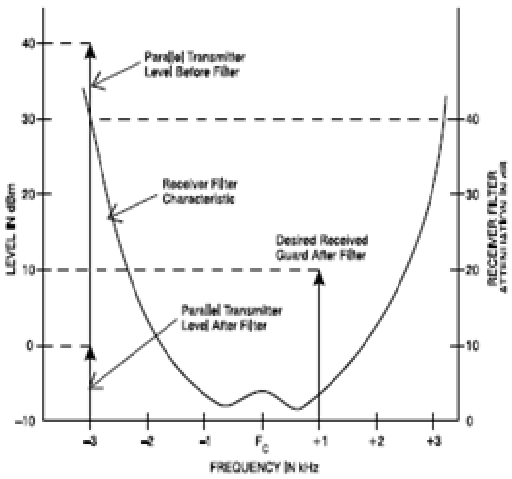

Figure 11. Interference between transmitters & receivers

XIV. CONCLUSIONS

According to aforementioned discussions, PLC method is suitable for data transfer because it reuses existing distribution lines and it is cost effective. However, using one line simultaneously as distribution line with high voltage and low frequency also as a communication channel with low voltage and high frequency, if required consideration, presented in this paper, are not included, transmitted data will contain considerable error. In overall it can be said that power line communication method is cost effective if all consideration are included.

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BIOGRAPHIES

Saman Rajebi was born in Tabriz, Iran in 1981.He received his B.Sc. degree in 2003 in electronic engineering from Tabriz university, Tabriz, Iran. And he received M.Sc. degree in communication engineering from Urmia university, Urmia, Iran. While pursuing his studies for MS, he worked for Urmia ICT center and Iranian telecommunication research center. He is already full-time teaching staff of Seraj higher education institute and he is member of executive committee of TPE conference. His interests are Power Line Communication, Microwave applications and modeling and simulation of communication systems and antenna designing.

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