

Redundancy in Coupling Power Line Carrier Channels to the Power Line

**A Working Group Report
From the H15 WG
Of the
H – Relaying Communications Subcommittee
IEEE Power and Energy Society/Power Systems Relaying Committee**

February 2011

Redundancy in Coupling Power Line Carrier Channels to the Power Line

A Working Group Report From the H15 WG

Participants

Roger Ray, Chairman
Bruce Pickett, Vice Chairman

Ray Fella	John Miller
Jerry Finley	Dan Reckerd
Terry Fix	Miriam Sanders
Ken Fodero	Don Sevcik
Bob Ince	Mark Simon
Jon Kellner	Eric Udren
Mike McDonald	Philip Winston

Redundancy in Coupling Power Line Carrier Channels to the Power Line

Introduction

This working group was formed in order to provide a report to the Relaying Communications Subcommittee on the redundancy of various coupling schemes in a power line carrier (PLC) based pilot protection system. Of particular interest, is when the protection is made up of two pilot schemes both of which use PLC for the protection channel. However, the information presented here is also applicable to redundancy within a single pilot protection environment.

This discussion is broken into several parts. First, is a basic discussion of coupling schemes and the important factor of efficiency. Second, is the presentation of various coupling methods. Last is a discussion on which schemes provide the best overall system redundancy as related to primary, secondary protection and the application of the carrier system and the common mode device failure that could render the carrier problematic or ineffective.

Some Background on Coupling Schemes as well as Pros & Cons

The goal in designing a protective relaying system PLC communications channel is to achieve a channel that will reliably communicate a protective system function over the power line to the remote end. Channel design is greatly dependant on the type of protective relay scheme used. Consideration is given to the operation of the channel during and after a fault. Many factors are considered in the design process but the common principal to all designs is to strive to use standard power line carrier transmitters to send the signal and to produce the best signal to noise ratio of power into the receiver at the remote end.

There are many components involved in a PLC channel. All the different individual components have losses associated with them. Figure 1 shows a typical PLC channel. The configuration of the equipment will affect the overall attenuation of the channel. The largest portion of the loss is typically the hybrid and coupling losses depending on the number of channels required.

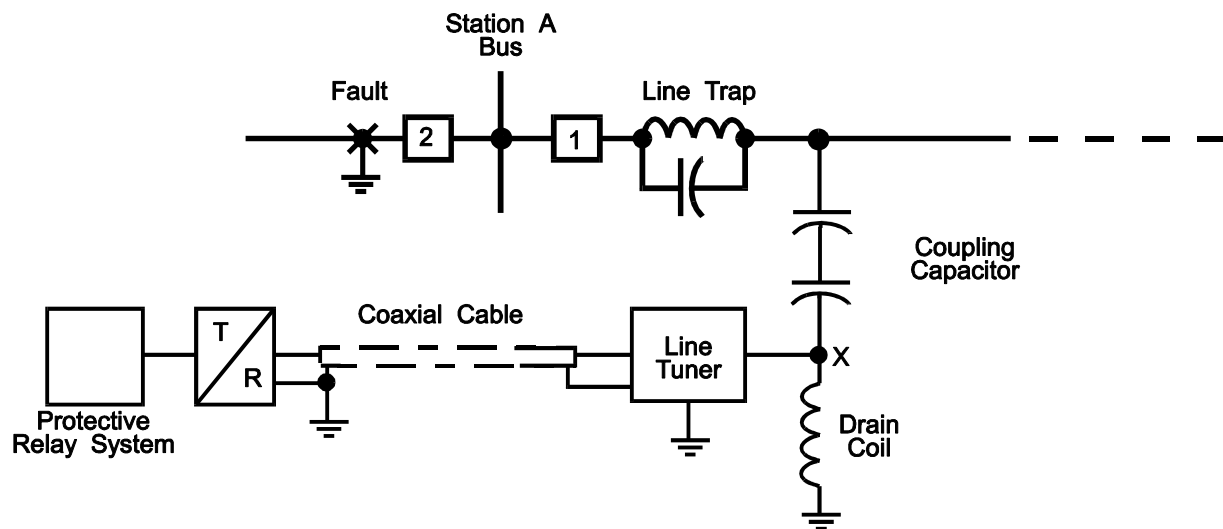


Figure 1 - Basic Power Line Carrier System

There are several methods used to determine the performance of the power line carrier coupling in the design of the power-line-carrier channel. The most accurate is modal analysis. Modal analysis can be

used to analytically determine the losses associated with the different coupling methods as well as the losses of the power line communications path. This technique is a mathematical process used to calculate the carrier current flow for the power line carrier channel. It is a process with similarities to symmetrical components which uses three networks for analysis of three phase power systems. Details of modal analysis and the discussion of these calculations is covered in Reference 1 and in Reference 2.

A significant consideration out of the many variables in the PLC channel design is the coupling method. The primary goal of a coupling scheme is to couple the transmitter energy onto the power line with the least possible losses. However, another goal, which is just as important, is that as much of the energy as possible be coupled as mode 1 component. The reason is that the mode 1 component has the least losses of the three transmission modes on the power line. It is beyond this report to go into an in depth discussion about modal analysis. A more in depth explanation can be found in the references given at the end of this report. The term mode 1 coupling efficiency is usually referred to as the ratio of the total power coupled to the power line to the power of mode 1 appearing on the line. This number is expressed in dB. Equation 1 below shows this relationship:

$$1) \quad \eta_1 = 10 \log \frac{P_1}{P_t}$$

Where η_1 is the Mode 1 Coupling efficiency, P_1 is the power in Mode 1 and P_t is the total input power to the line. Thus, as an example, if P_1 is half the value of P_t then η_1 is -3 dB. Table 1 below shows the calculated and measured (where available) values of coupling efficiencies for various types of coupling schemes. *If there is a roll of two phases just as the line leaves the substation, it should be noted that when the paper discusses outside or center phase for the coupling of a coupling scheme it is talking about the phase positions on the line side of the roll.*

As with most systems, there is more than one way to couple the carrier to the power-line. The deciding factors may be economics and Mode 1 coupling efficiency. The best Mode 1 coupling efficiency may be too expensive to justify for the line being protected so the next best one may be the preference. Most all lower voltage lines (<230 kV) use single-phase-to-ground coupling, requiring only one set of coupling equipment (line tuner, coupling capacitor and line trap). However, for EHV lines (230 kV & higher) dependability and redundancy requirements may dictate multi-phase coupling. Multi-phase coupling will require multiple sets of coupling equipment. The various coupling methods are compared in Table 1 (ranked in order of coupling efficiency).

Table 1 - Mode 1 Coupling Efficiencies

Coupled Phases (unused phases grounded)	Calculated Mode 1 Coupling Efficiency (dB)	Measured Efficiency (dB)
Three Phase (Mode)1	0	
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

- Out on two outer phases, in on the center phase (Mode 1 coupling) (Refer to Figure 2).
- Center phase-to-outer phase (push-pull) (Refer to Figure 3).
- Center phase-to-ground (Refer to Figure 4).
- Outer phase-to-outer phase with ground return (push-push) (Refer to Figure 5).
- Outer phase-to-ground (Refer to Figure 6).

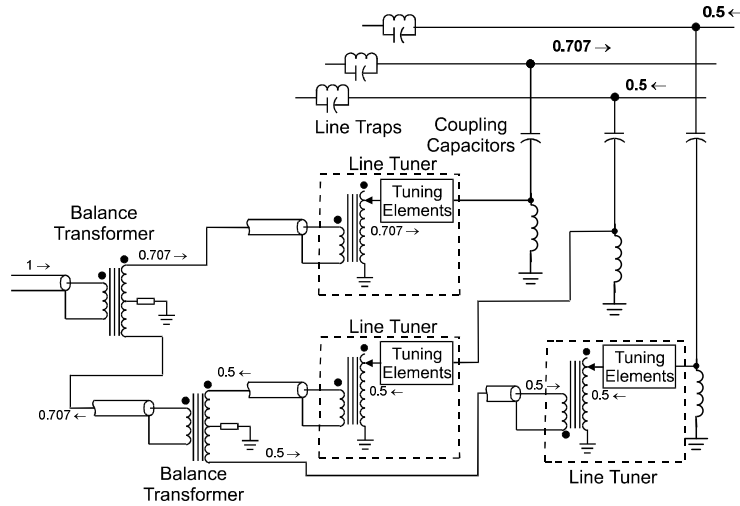


Figure 2 – Mode 1 Coupling

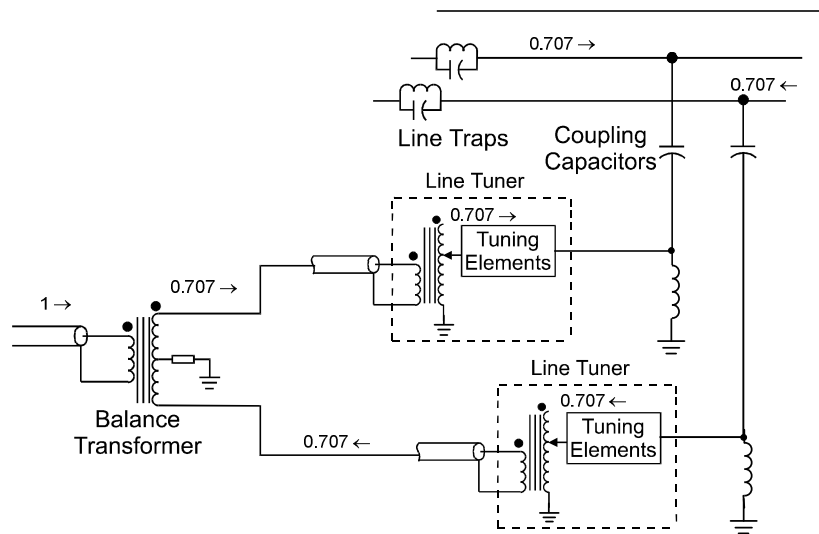


Figure 3 - Center phase-to-outer phase Coupling

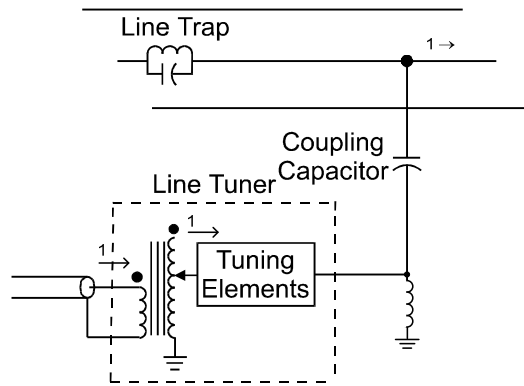


Figure 4 – Center Phase-to-Ground Coupling

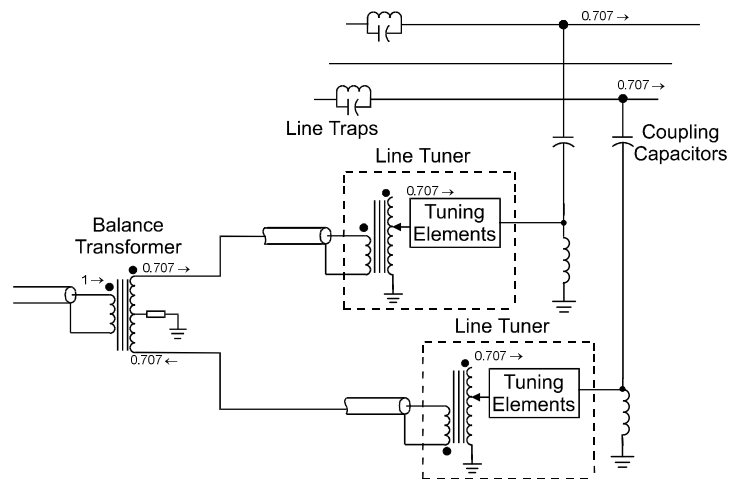


Figure 5 – Outer Phase-to-Outer Phase (with Ground Return)

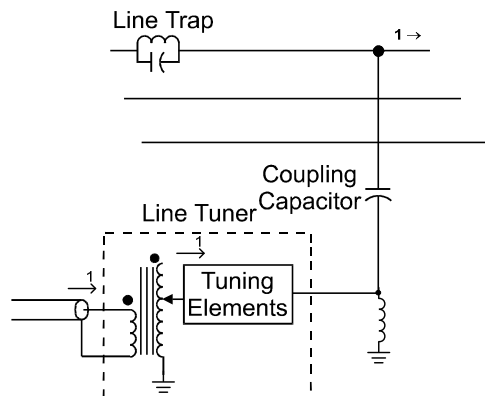


Figure 6 – Outer Phase-to-Ground

Description & Discussion of Different Coupling Methods

Mode 1 Coupling

Refer to Figure 2. This coupling method is the most efficient and presents the lowest in losses of all PLC coupling configurations. Mode 1 coupling requires the use of wave traps, coupling capacitors and line

tuners on all three phases. The coupling scheme shown in Figure 2 shows the current returning in the center phase to be 1.414 times the current out the outer phases. This is not exactly Mode 1 coupling, but it is very close. It has a mode 1 coupling efficiency of 99% or better. It is the most expensive type of coupling but offers the lowest coupling loss and provides the most channel redundancy of all the coupling methods. For some EHV lines, mode 1 coupling can be justified, even though it requires line traps, coupling capacitors and line tuners for all three phases. There are two levels of backup for component failure. With the loss of one phase of coupling the scheme will revert to phase-to-phase coupling method. With the loss of two phases of coupling the scheme reverts to a phase-to-ground coupling method.

Phase-to-Phase Coupling

Refer to Figure 3 and Figure 5. Phase-to-phase coupling requires wave traps, coupling capacitors, and line tuners on two phases,. This coupling method provides a dependable channel for relay schemes that are more secure and rely on a signal getting through to the remote end of the line to trip. Since most faults are line to ground, the chances for a signal getting through during a fault is greater with this type of coupling allowing the protection engineer to use more secure type of relay schemes.

Phase-to-phase coupling also provides redundancy for failure of a single tuning component or taking the tuner on one phase out-of-service. Loss of a component on one phase will cause a drop in signal but will not cause a loss of the channels. Using this coupling method with two independent pilot schemes provides a combination of good reliability and reasonable complexity. Even with the loss of one of the phase paths, all of the channels will be functional.

Phase-to-phase coupling has approximately 2 dB more coupling loss than a mode 1 coupling method but requires 1/3 less equipment. It reduces the amount of equipment required to install and maintain but provides a redundant communication path for the protective relaying functions.

Phase-to-Ground Coupling

Refer to Figure 4 and Figure 6. This is the simplest and least cost coupling method and requires the least equipment. One wave trap, one coupling capacitor and one line tuner are required for coupling. Center-phase-to-ground coupling method adds about 3 dB loss over mode 1 coupling but has 2/3 less equipment. Outer-phase-to-ground coupling adds considerably more losses. For the lowest attenuation of this type of coupling, the center phase is used. This is also the least reliable coupling method. Failure of any component will result in the failure of the channel. This failure may cause the pilot portion of the relay system to not operate correctly. Multiple channels may be coupled using this method by using auxiliary tuning components and either wide band or dual frequency wave traps and line tuners.

Single phase-to-ground coupling is typically used with a directional comparison blocking (DCB) protection scheme. The protection scheme sends a block trip signal to the remote end for external faults. For a fault on the protected line section no blocking signal is sent, when a directional relay is utilized for the carrier start function, and both ends of the line will trip. Failure of the block signal to reach the remote end for an external fault (that is within the reach of the overreaching relay at the remote end) will cause an over trip but the scheme is very dependable as it will always trip for internal faults.

Two phase-to-ground coupling schemes can be used to provide channels for dual pilot protection schemes. The advantage of using two single phase-to-ground coupling schemes is that it provides two independent paths that cannot be degraded by a single component failure. If a component fails it will only affect one channel leaving the other channel operating normally. The losses will be somewhat higher than other coupling schemes but on shorter lines with enough signal margin, this method provides redundancy and low cost for dependable type protection schemes.

Redundancy Considerations

The design and configuration of the PLC channel is greatly dependant on the requirements of the protective relay system that will be used to protect the line, the stability requirements of the area, and the length and voltage of the protected line. A single pilot DCB relay scheme on a medium length 115 kV to 169 kV line could use a center phase-to-ground coupling method with single frequency wave traps and tuners. On the other end of the spectrum, a long 500 kV line connecting a power plant to the transmission system may require multiple secure protective relaying schemes which would lead to more dependable PLC channel requirements. Here mode 1 coupling with multiple channels for the different relay functions would be justified.

The protection engineer obtains the power system stability requirements and critical fault clearing times from the planning engineers to determine the protective system scheme reliability requirements. The ability to obtain outages for maintenance and the criticality of the protected line segment will contribute to the determination of these protective scheme reliability requirements. Once these reliability requirements have been determined, if PLC is to be used for relay communications, then the PLC system design parameters can be determined. The number of carrier channels required as well as the coupling configuration and transmitter power levels will depend on these reliability requirements as well as the transmission line configuration and length.

Best Coupling Schemes for Redundancy

One would think that using two totally separate channels (one for each of the pilot relay systems) would result in the most redundancy possible for PLC. One system would be coupled on one phase of a three-phase transmission line and the other on another phase. An example of this coupling is a combination of Figure 4 and Figure 6. However, this creates two concerns – the first being that it is not the best possible coupling for the system on the outside phase (refer to Table 1) and the second one being that there isn't enough isolation between transmitters since there is little to no isolation between the two phases (refer to Figure 7) and thus the two transmitters are not isolated from each other. This lack of isolation will cause intermodulation distortion. Intermodulation distortion creates new frequencies to interfere with other channels on the same line or adjacent lines. Also from a redundancy point of view, if one line tuner or coax fails, the channel will fail and the pilot portion of the relay system may not operate correctly.

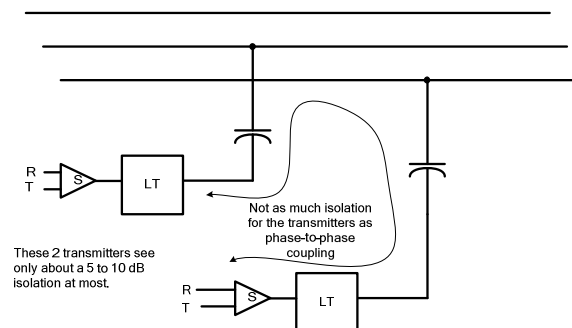


Figure 7 – Two Independent PLC Channels, each coupled phase to ground.

A better approach both from an isolation and redundancy point of view is to use phase-to-phase coupling (refer to Figure 3). Possible fully redundant phase-to-phase coupling schemes are shown in

Figure 8 and Figure 9. These coupling schemes provide the second best mode-1 coupling efficiency (refer to Table 1).

There are two wave traps, coupling capacitors, and line tuners used for this method, with the addition of a balancing transformer and various hybrid complements. Even though there are more losses in the transmitter path, there is also much better isolation between the two transmitters. This means no intermodulation distortion to interfere with other PLC channels. While the additional hybrids add more components to the overall complement of equipment, as well as a common signal path (in the control house), these devices are passive devices and failures are rare. More importantly from a redundancy point of view, for the failure of one line tuner or coax, both signals are still being coupled to one of the phases and there is not a complete loss of one channel, just a reduction in signal strength. Since most faults are outer phase-to-ground, coupling to the center phase, provides some protection against total loss of channel due to lightning strikes. It should be noted in Figure 8, that to gain full benefit of this coupling scheme the hybrids and common path coaxial cables are located in the control house and two coaxial cables run to the two line tuners in the switchyard. In Figure 9 to gain optimum redundancy, the balance transformers need to be mounted in the control house and four coaxial cables need to be run to the two line tuners. If the balance transformers in Figures 8 and 9 are mounted in a line tuner in the switchyard, redundancy is reduced.

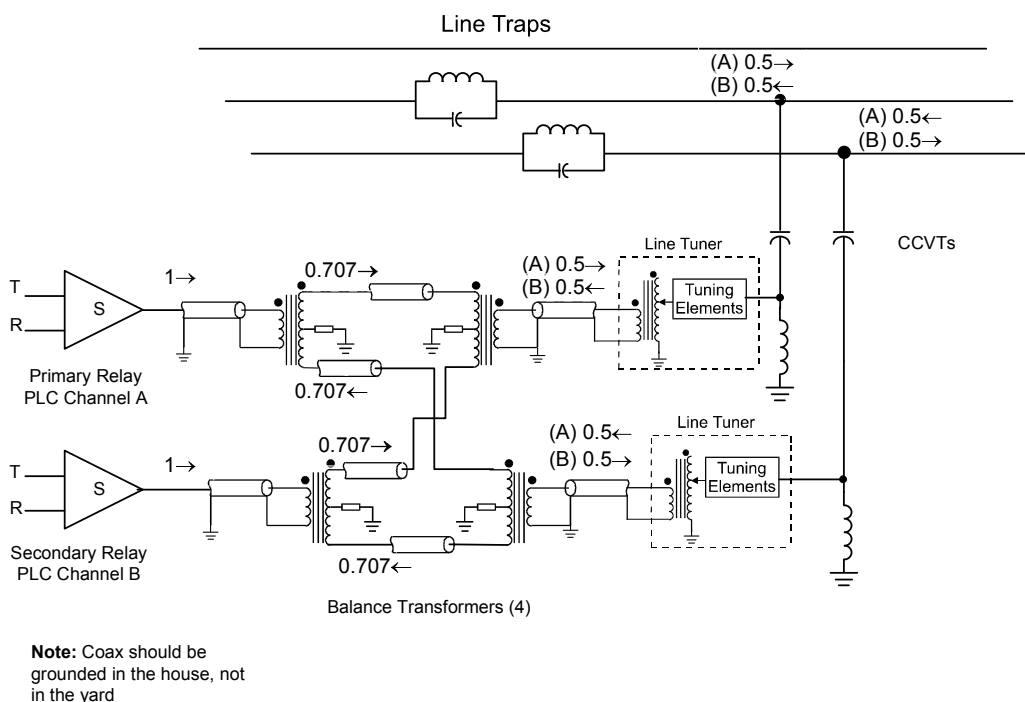


Figure 8 - Two PLC Channels, coupled together via phase to phase Using either Single Frequency or Wideband Tuners

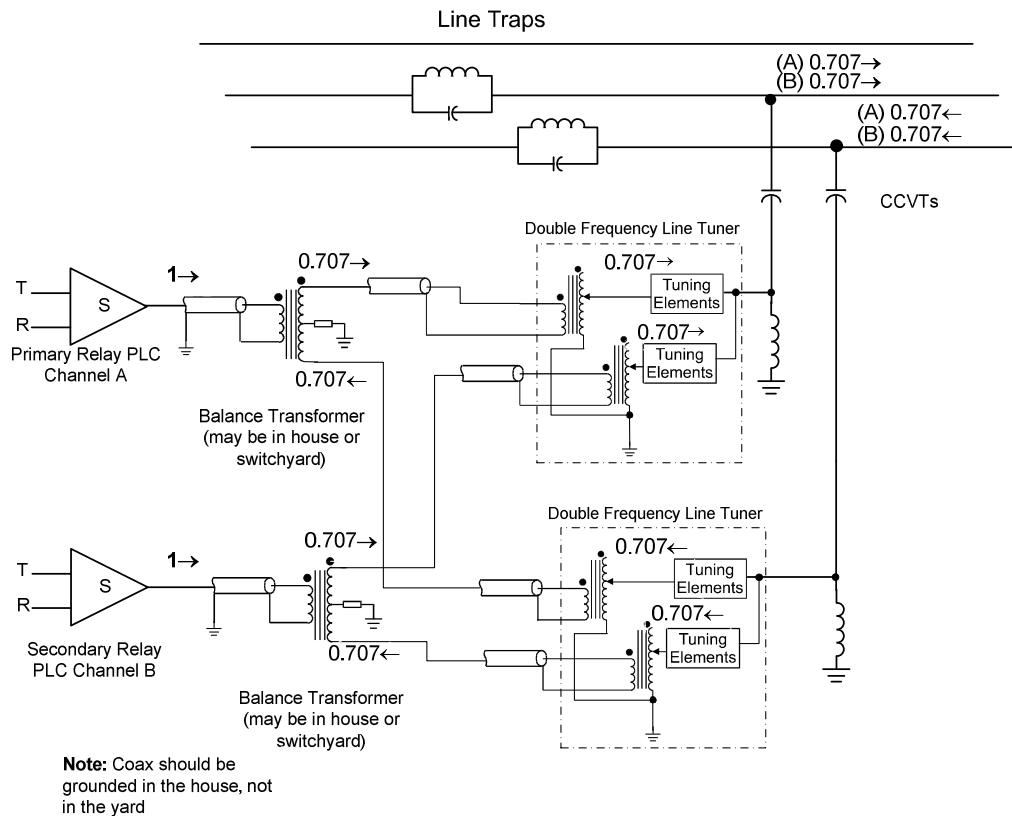


Figure 9 - Two PLC Channels, coupled together via phase to phase Using Two-Frequency Tuners

On lines where two or more pilot schemes are utilized, mode 1 coupling provides the most redundancy of all of the other coupling methods while also providing the lowest losses to couple the PLC transmitters to the power line. This coupling method would be selected for long lines or lines where the redundancy provided would justify the extra initial equipment costs and additional maintenance costs. The channel will be available during most faults so a secure relay scheme could be used for line protection.

When mode 1 coupling is utilized (refer to Figure 10) the mode 1 coupling efficiency (refer to Table 1) will be almost 100%. Mode 1 coupling uses all three phases and requires three wave traps, coupling capacitors, and line tuners and additional hybrids and balancing transformers. The balance transformers, hybrids and common path coaxial cables should be in the control house, and therefore, there will be three coaxial cable runs from the control house to the switchyard. There is one point of failure, the coax in the control house, but it isn't exposed to the elements and should be a short run.

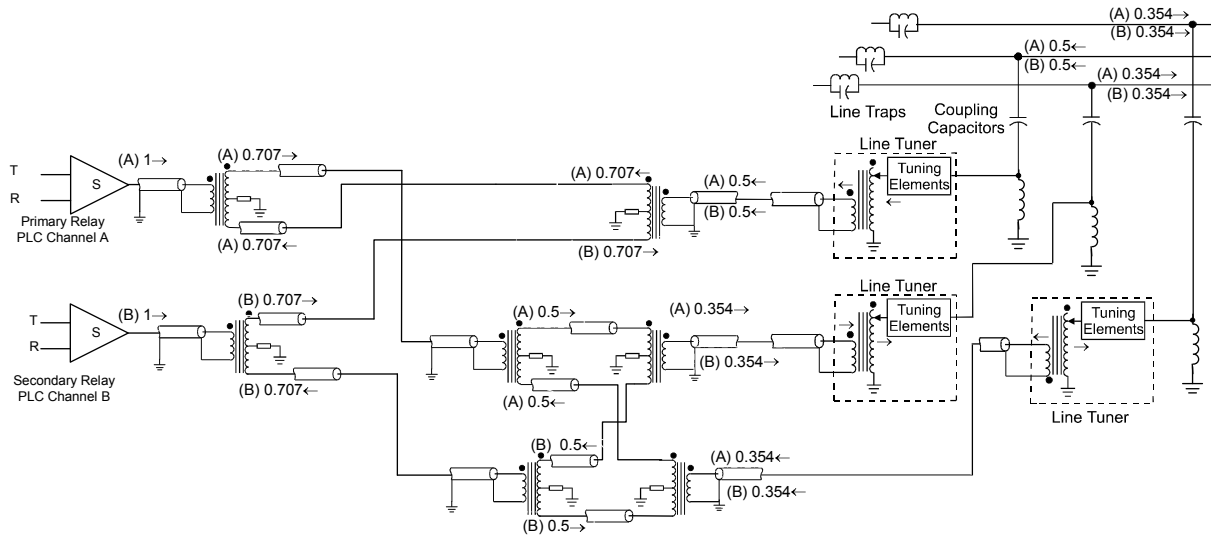


Figure 10 – Two PLC Channels, coupled together via Mode 1 coupling using either single-frequency or Wideband Tuners

Signal Alarm Considerations

The loss of any one phase in a phase-to-phase or three phase redundant carrier scheme will cause a signal loss. This signal loss could be as much as 6 dB. The normal setting for low level alarms on most receivers is 10 dB. With this setting, the loss of a signal path would not bring in a low signal alarm. Resetting the alarm level to come in at a signal loss of 5 dB may be more appropriate for redundant carrier schemes using phase-to-phase or three phase coupling.

References

- 1 - IEEE 643-2004 - IEEE Guide for Power-Line Carrier Applications
- 2 - Power-Line Carrier Channel & Application Considerations for Transmission Line Relaying by Miriam Sanders and Roger Ray, May 1996
- 3 - Relaying Communications Channel Application Guide - Trench Electric
- 4 - A NERC Technical Paper - Protection System Reliability Redundancy of Protection System Elements – January 2009