Directional Comparison Blocking System Fundamentals

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Introduction

This paper discusses the fundamentals of directional comparison blocking schemes (DCB), which is one of several directional comparison communication assisted schemes. DCB, however, is specifically intended to be used with systems where communications is less secure (likely to be lost) during line fault conditions. The paper addresses the operational concept of the DCB scheme using "on/off" power line carrier, and issues pertaining to reliability and performance. This includes the pros and cons of using "non-directional" or "directional" start of the blocking signal, the blocking coordination timer, carrier hole issues and mitigation, and relevant logic. The paper will help the reader to develop an understanding that an apparently simple DCB scheme requires a deeper understanding to insure optimum implementation.

Terms

The following terms or acronyms are defined as to how they are used in this paper to provide the reader a clearer understanding.

Pilot – A scheme utilizing communication of information between source terminals of the transmission line. It is also known as a communications assisted scheme.

PLC – Power Line Carrier - a pilot scheme using the power line as the signal medium.

FP – A forward directional protection element (e.g. overcurrent or impedance function) used in a DCB scheme to detect a forward fault.

F – The suffix on an IEEE relay number defined in C37.2 to indicate a protection element that detects a forward fault (e.g. 21F, 67NF).

RP – A reverse directional protection element (e.g. overcurrent or impedance function) used in a DCB scheme to detect a reverse fault.

R – The suffix on an IEEE relay number defined in C37.2 to indicate a protection element that detects a reverse fault (e.g. 21R, 67NR).

BLOCK – A carrier signal received from the remote terminal(s) that is used to block tripping of the forward pilot supervised protection elements.

I0 – Normally a low set 50N unit, but used here as a generic non-directional start.

Directional Comparison

Directional Comparison relaying interprets the direction to the fault during a power system fault as an internal or external fault. If the fault power is detected to be flowing inward at all line terminals, the fault is internal. An external fault is when the fault direction is out from the line at one terminal and into the line at one other terminal. The relay system is to trip for an internal fault and block tripping for an external fault. Several types of directional comparison system are employed by the utilities. DCB systems are widely used and will be covered in more detail in this paper. Other directional comparison systems include permissive overreaching or underreaching systems and directional comparison unblocking or hybrid systems. It is left to the curious reader to research these other pilot schemes further.

Directional comparison systems can utilize Power-line Carrier (PLC) channels for its communication channel, due to its simplicity and economics. Since the transmission media is already present (the transmission line), only a transceiver and coupling equipment are needed.

Directional Comparison Blocking

The DCB system basic elements are illustrated in Figure 1. At both terminals, the forward pilot protection elements FP-A and FP-B (with elements to cover both phase and ground faults) must be forward directional and set to overreach the forward remote terminal; that is, they must be set to operate for all internal faults with adequate margin. For example, nominal settings of the distance units are 120 to 150 percent of the line. Overcurrent units should generally extend this far or beyond. The BLOCK start units (RP-A and RP-B) are directional, but may include non-directional elements for specific schemes, and must reach farther, or be set more sensitively, than the remote forward trip units. Thus RP-A must be set more sensitively than FP-B or reach farther behind bus C. Likewise, RP-B must be set more sensitively than FP-A or reach farther behind bus D. In any case, the RP and FP relay elements should be similar in function. If the forward trip element (FP) is a forward directional overcurrent ground relay, the BLOCK start (RP) ground relay should be a similar directional or non-directional overcurrent unit. The same principle applies for the protection elements that detect multi-phase faults



Figure 1. Basic directional comparison blocking system

The reverse looking element (RP) acts as the start input to the keying logic of the transmitter. The forward looking element (FP) acts as the stop input to the transmitter keying logic. This is illustrated in Figure 2. Utilizing a normally closed contact for the start function as in Figure 2(a) reduces issues with contact bounce as well as providing for a continuous monitoring of the integrity of the start circuit. When a normally open contact is desired, then the transmitter keying logic becomes as shown in 2(b). Whichever logic is used, care must be taken to insure that the STOP input has priority, so as to allow tripping for an internal fault, no matter what else is occurring on the relay system.



Figure 2. Transmitter keying logics

When the on-off power line carrier is used with these schemes, except for possible auxiliary functions, no signal is normally transmitted, since the RP units are generally not picked up (no fault condition).

Basic DCB tripping logic is illustrated in Figure 3. The forward looking element will trip should a block signal not be received from the pilot channel before the Coordination Timer has expired. Operation of the DCB scheme shown in Figure 1 is given in Table 1 for both external and internal faults.



Figure 3. A Basic DCB trip logic – X = channel time + margin, normally 6 to 16 ms.

Type of Fault	Events at Station C	Events at Station D
External (F _{EXT}) For external faults, the timer x/o assures that time is allowed for a blocking signal to be received.	FP-A operates; RP-A does not see fault. Blocking signal received from station D and signal negates AND. No trip.	RP-B operates to key transmitter. Blocking signal sent to station C. FP-B does not see fault. No trip.
Internal (F _{INT})	FP-A operates; RP-A may or may not operate,* but FP-A operation prevents (stops) transmission of a blocking signal. Breaker A tripped.	FP-B operates, RP-B may or may not operate,* but FP-B operation prevents (stops) transmission of a blocking signal. Breaker B tripped.

*Depends on use of directional or non-directional starting RP unit.

The blocking scheme is 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. So there is no concern about transmitting a signal over a faulted line. Over tripping will occur, however, if the channel fails or is not established for external faults within the reach of the FP trip fault detectors. Since the carrier transmitter is normally OFF, or non-transmitting, channel failure cannot be detected until a fault occurs to test the system. This limitation can be mitigated by using a "checkback" system as described in a later section.

It is desirable to trip the faulted transmission line as soon as practical so therefore high speed or wide band ON-OFF channels are typically used. PLC channels are typically in the order of 4 ms or less, with propagation delay additional. Propagation delay is dependent upon the length of the line and is typically 1 to 2 ms for lines over 100 miles.

Reliability

According to the IEEE dictionary, reliability is the ability of a system or component to perform its required functions under stated conditions for a specified period of time. In the protection world reliability is a dual component qualification of the system performance. One component – dependability - is the ability of the system to operate correctly for an internal fault. The other component is security – the ability of the system to not misoperate for an external fault. These two qualifications are mutually exclusive – unable to have a system that is both 100% dependable and 100% secure. It is a balance between the two that protection systems strive to achieve. When designing protection systems, the protection engineer must be cognizant of the detrimental effect of failure to operate versus misoperation. If the relay system fails to operate for an internal fault, and backup systems must operate to clear the fault, what is the exposure? Or if the relay system misoperates (trips for an external fault), what are the consequences? It is the protection engineer's job to balance this.

DCB systems are very dependable systems. This is due to the fact that the channel is not required to trip for an internal fault. DCB systems are not secure systems at times due to the fact that if the channel is not available, the system will trip for an external fault. Should a secure system be desired, a directional comparison unblock system may be better suited for the line relaying system.

The major components of a PLC channel are shown in Figure 4. PLC signals are high-frequency, low voltage signals and are applied to a high voltage, low frequency transmission line. The goal of the PLC coupling equipment is to get the carrier signal onto the high voltage line without damaging the low-voltage electronic transmitters and receivers. Once the signal is on the power line it must be directed on the proper path in order for it to be received at the remote line terminal.



Figure 4. PLC channel components

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 means there is a large distance between the carrier 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 (ccvt). If there is more than one transmitter involved per terminal the signal must go through isolation circuits, typically called hybrids, before connection to the line tuner.

Hybrids & Filters

The purpose of a hybrid circuit 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 high-frequency carrier energy to the transmission line and a high

impedance path to the low-frequency power 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 high impedance to the power frequency energy. Even though the coupling capacitor has high impedance at power frequency, 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 a characteristic impedance of 150 to 500 ohms (not to be confused with fundamental frequency).

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 that would affect signal transmission. 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 high impedance at its tuned frequency, and it then causes most of the carrier energy to flow toward the remote line terminal, blocking it from going to the local bus. The coil of the line trap provides a low impedance path for the flow of the power frequency energy. Since the fundamental frequency power flow is rather large at times, the coil used in a line trap must have the appropriate current rating and are 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 can be found in several of the references at the end of the paper.

On/Off PLC Equipment

Several types of signal modulation are available that are applicable to transmission line protection systems. The basic signal is a sine wave, which is then changed, or modulated, in order to produce either a block (no-trip) signal in a DCB scheme or a trip (permission) signal in other types of pilot schemes. The modulations include amplitude modulation and frequency modulation. Amplitude modulation has a constant frequency, and only the signal level (amplitude) is modified to communicate a change of state. Frequency modulation can have two or three distinct frequencies such as guard, trip and some cases another trip frequency. Normally the amplitude will also be amplified, or boosted, during a trip condition. For DCB signals, most applications use amplitude

modulation, which is further simplified to be an On-Off type of signaling. The signal is normally off and is only keyed on during an external fault to prevent tripping for an out-of-zone fault. The on-off type of modulation does not require any receiver logic other than a detector circuit to receive the blocking signal, since it does not need to distinguish between two or three frequency signals as a frequency modulated system would need.

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, two of the three transmitters are offset by ±100 Hz. The three frequencies should be:

 $\begin{array}{l} f_{C} \\ f_{C}-100 \; Hz \\ f_{C}+100 \; Hz \end{array}$

What are Carrier holes?

As mentioned before, the PLC channel signal is not required for tripping for an internal fault, but is required to block tripping for an external or out of zone fault. Therefore, the integrity of the PLC channel is important to prevent misoperation. Since the signal is not normally transmitted, it is advantageous to have some sort of automatic periodic testing of the channel. This is normally done with either a checkback system in the channel equipment itself, through the line relay doing the protection function, or with an external stand-alone device. The time interval is usually determined by the experience of the local utility and current practices, but may typically be done daily or weekly. This periodic testing checks the ability of the system to key the transmitter on and the ability to transmit the signal, the receiver to receive and detect the signal during the normal (non-faulted) state of the transmission line. What this testing does not check is the ability of the system to properly perform during the stress of a transmission line fault, either internal or external.

Faults produce transients on the transmission line that are orders of magnitude greater than the normal voltages and currents. Transients can also be produced during switching operations and breaker opening operations. The transients typically are short in duration, high in frequency and high in noise. These qualities may or may not affect the PLC channel. Sometimes faults will totally short out the PLC signal if the external fault is close in to either terminal but normally there will be some signal received at the remote end, even during an internal fault. Protection systems are designed to tolerate loss of the PLC signal– as the blocking signal is not required to trip for an internal fault – erring on the side of dependability. But if the signal is not able to be transmitted or received for an external fault we could have an over trip condition which is most undesirable. This can occur due to what in relay jargon is commonly called "carrier holes".

What is a carrier hole? It is when the blocking signal disappears during a fault on an external transmission line due to something in the PLC system shorting to ground. There are several culprits of carrier holes in the PLC transmission path. The signal is propagated from the transmitter through a coax or triax cable to the line tuner, through the coupling capacitor to the transmission line itself. Flash-overs of the signal to ground can occur at several of these places in the channel. It is the "weakest link" that causes the issue. As coax ages, the insulation begins to

degrade, allowing a path from the center conductor to the grounded shield, allowing a flash-over when stressed. This will result in a loss of signal or carrier hole for the time the flash-over is present.

In the coupling capacitor and in the line tuner, there are protective units, made up of protective air gaps (spaced electrodes), gas tube or other limitation devices, and an RF grounding switch. In the ccvt, the protective unit is across the drain coil. The line tuner may also have a secondary drain coil, in which the protective unit is across that as well, but otherwise, the protective unit is still there, along with an RF grounding switch. Figure 5 shows the protective gaps.

The protective gaps serve to provide a low impedance path to ground for surges due to transients, thereby preventing high level surges from getting into the electronics of the PLC channel as well as protecting the drain coil in the ccvt. The goal of the protective gap is to arc over quickly and "seal-off" or extinguish the arc expediently. The gap should arc and seal-off within 1 to 2 milliseconds, so fast that the transmission line protection relay has not had time to process the fault data and take action for the fault. The flashover point is defined in the ANSI/NEMA C93 standards to be above 2.5 kV RMS at power frequency voltage and below 85% of the BIL rating of the device (10 kV for Line Tuners, ccvt's). Also, these surges are limited by any adjacent lightning arresters.



Figure 5. Protective gaps in line tuner and ccvt

Other areas of concern may be what occur during a ground potential rise caused by the fault, what about Transient Recovery Voltage capacitors, what about series of shunt capacitors and their interaction with the ccvt's capacitance? There may be other areas to consider.

Maintenance is the key for preventing carrier holes. The protective gaps need to be routinely cleaned and re-adjusted for proper flash-over voltage and coax cables should be periodically tested and replaced if necessary. Every time there is a transient on the transmission line, the protective gap will more than likely flash-over, which in turn builds up carbon, thereby decreasing the flash-over voltage of the gap. So that next time, it may flash-over sooner than expected and not seal-off in time, thereby creating a carrier hole. *Maintenance of the gaps will greatly improve the overall security of the channel and the protection system.* Checkback systems do not detect issues with carrier holes since they are run during non-fault conditions.

It would appear that there is an increase in the occurrence of "carrier holes", but it is probably more due to the increase of information that is now available with the microprocessor-based devices and the ability to obtain sequence of events out of these devices.

How long are carrier holes?

Carrier holes range from around 2 ms to several or more cycles depending on the state of the carrier channel apparatus protective gaps and the voltage transients produced during faults. Experience shows that carrier holes are more often than not less than ½ cycle in duration. Experience also shows that "stuff" happens and much larger carrier holes may occur. The following cases are provided as real world examples.

Events 1 & 2

Events 1 and 2 are shown in Figures 6 and 7, respectively. These events show a very common occurrence of repeated carrier holes in the BLOCK signal of a short duration. Keep in mind that the resolution (sampling and/or computation frequency) affects the apparent length of the carrier hole, which may appear slightly longer than they actually are. In any case the holes in these two events are less than ½ cycle in duration.

In event 1 a fault external to the protected line occurs and the carrier holes begin approximately 3 cycles after fault inception. The FP signal has been asserted for a while so the relay asserts its TRIP signal immediately with the start of the first carrier hole (BLOCK signal drops out). It is speculated that the remote line's breaker is opening thus generating the voltage transients that initiate the insulation breakdown and resulting carrier holes. There is no corroborating data from the remote terminals. Note that the reoccurring holes align nearly with the minimum and maximum 3I0 peaks. Issues were reportedly found with the local end PLC equipment.



Figure 6. Event 1 fault record of an incorrect trip for a forward external fault

In event 2 the carrier holes begin approximately 2.5 cycles after fault inception. The FP (67N2) signal has been operated for a while so the relay asserts its TRIP signal immediately with the start of the first carrier hole. It is again speculated that the remote line's breaker is opening thus generating the voltage transients that initiate the insulation breakdown and resulting carrier holes. Higher frequency voltage transients cannot be observed on digital fault records recorded with lower sampling frequencies. There is no corroborative data from the remote terminals. Note that the reoccurring holes align somewhat to the minimum and maximum 310 peaks, but not as close as in Event 1. The carrier holes continue in the BLOCK signal after breaker opening and are most probably the result of breaker opening transients. In this instance a spark gap in the remote location's tuner reportedly had "spit" marks, clear evidence of operation. Also, the tuner ground was not very good.



Figure 7. Event 2 fault record of an incorrect trip for a forward remote fault

The operation of a DCB scheme is such that the relay(s) at the line terminal(s) remote from the external fault will observe this condition (holes) when it occurs, but the culprit PLC apparatus may exist at any of the line terminals. It is hypothesized that close alignment between the carrier holes and the 310 peaks as in Figure 6 <u>indicate a local end issue</u>, and where carrier holes do not align nearly as well, as in Figure 7, then the issue <u>may be at the remote end</u>. This is the case for these two events. The different alignment results being primarily influenced by 310 phase angle shift across the line and carrier channel time as well as digital input sampling resolution. It is not our intent to study this phenomenon further, but merely to suggest a starting point for inspection and correction for all line terminal apparatuses.

Event 3

Event 3 shows the occurrence of carrier holes at fault inception, remote line clearing and finally at local clearing, which however is of no consequence. The carrier hole pattern does not resemble that of Events 1 and 2. Consider the one-line and the relay's digital fault record of Figure 8.



Figure 8. Event 3 fault record of an incorrect trip for a forward remote fault showing the occurrence of a large carrier hole

There are two transmission lines connected to a major generation substation as shown on the system one-line. A fault occurs on Line 2, which appropriately trips. Line 1 also trips due to incorrect operation of a DCB pilot scheme. This is clearly shown in the fault record taken from the relay at the local end.

Hole-1 in the BLOCK signal occurs just after fault inception and is 6.24 ms long. It occurs before the FP - forward pilot ground overcurrent element, 67N FWD, operates, therefore, no tripping. Hole-2 in the BLOCK signal (more like a canyon) occurs just after the fault clearing of Line 2 begins and lasts for 31.2 ms. Line 2 fault clearing is identified by wave form discontinuities on IB, IC and IPol. With 67N FWD operated and BLOCK not asserted tripping with PILOT BLOCK TRIP occurs 10.4 ms into Hole-2. The Line 1 terminal at the remote end continues sending the block signal to the local end after local end tripping as indicated by CC BLOCK Receive. With breaker opening at the local end high frequency voltage transients are produced and observed on the fault record. The maximum transient voltage cannot be determined due to analog input filtering (anti-aliasing) and the resolution (samples/cycle) of the fault record. Hole-3 in the BLOCK signal occurs just after the beginning of the breaker opening transients. Although Hole-3 occurs after line clearing it illustrates the cause and effect of voltage transients and carrier holes.

Logic

Voltage transients that cause carrier holes in a transmission line PLC signal are generally those generated at fault inceptions, fault clearing (breaker opening) on adjacent transmission lines and local breaker clearing. Holes produced at fault inception do not usually result in a misoperation because they occur well within the first one half to one cycle after the fault inception and well before the overreaching FP trip has operated or has been released to trip by the blocking coordination timer. Holes produced at remote breaker clearing usually occur from 3 to 7 cycles after the fault inception and well after the FP has operated and been released by the blocking coordination timer. When these "late" holes occur tripping occurs immediately unless there is some additional logic employed to mask the holes.

Coordination and Blocking Signal Extension Timer

One form of logic employed to mask carrier holes is the simple logic of Figure 3. If a BLOCK signal is being received and drops out due to a carrier hole, the coordination timer - in this case working as a blocking signal extension timer - starts and TRIP will only be asserted if the carrier hole time is larger than the set coordination time. In this case the coordination timer serves to mask carrier holes where tripping is not desired. Therefore, assurances must be made that the coordination timer is set with a longer time than the maximum expected or accepted carrier hole time. This may require setting the coordination timer of Figure 3 would have to be set to a minimum of 2 cycles to mask the large carrier hole of Event 3 described above. This would delay pilot tripping for an internal fault which may or may not be acceptable depending on the power system fault clearing time requirements. Separation of coordination and blocking extension timers might be considered if there is an ability to tolerate large carrier holes.

Separation of Coordination and Blocking Signal Extension Timers

Another logic, which is commonly used to separate the coordination and hole masking timers, is shown in Figure 9. The separation of the timers allows setting the signal extension time to mask holes to any value and it will not affect the coordination timer's delay of blocking pilot trip.



Figure 9. Basic Trip Logic with separate coordination and blocking extension timers logic – Y- block signal extension time to mask carrier holes.

Reliability: Security and Dependability

DCB operating scheme security and dependable fast tripping are at odds and, therefore, there are several factors to consider when applying blocking coordination and extension timers and how the blocking channel is started, maintained, and stopped. What we will find is that no one way is always the best approach. In some cases there are machine stability requirements that prompt us to have as fast clearing as possible for faults down the entire length of the line. In other cases we may need fast clearing but not ultra-fast, especially in light of the fact that the fault will be within the zone 1 elements of one end. These and other factors will impact our decision on how we handle channel starting, stopping and carrier holes.

Channel Starting

The traditional DCB scheme uses a "non-directional" start philosophy. Initially with electromechanical and solid state relay systems a simple ground overcurrent element, 50N, was and still is set to assert and start the blocking signal without regard to where the fault is located (internal or external). This allows a very fast start of the blocking signal with the obvious advantage that for external faults the remote end relay will receive a blocking signal as quickly as possible. The non-directional start was generally noted as 10 to distinguish it from other 50N protection functions. If the fault is seen by a local forward tripping element the block signal is immediately stopped. Because the directionally supervised forward tripping element is slower than the non-directional overcurrent, there will always be an initial blocking signal pulse (or "blip" of carrier) sent to the remote end. Basic DCB channel BLOCK signal start and stop logic are shown in Figure 10.



(a) Basic start and signal continuation logic



Figure 10. Basic start and stop logic -- OPEN TERMINAL – breaker(s) or line disconnects are open for a while, START – transmit blocking signal, STOP – stop transmitting block signal, C – Block signal continuation time (2 – 5 cycles), HS TRIP – includes only high speed direct and pilot tripping

With the advent of microprocessor technology in the mid 1980s the operation of 50N (or 50Q) microprocessor based units performed slower than the electromechanical or solid-state counterparts so voltage and current change detectors (dv/dt, di/dt), which could detect fault inception and start the block signal as fast as 2 ms, were introduced to give the 50 units a "kick-start" on sending the BLOCKING signal. This even further minimizes the coordination delay time requirements and, with the coordination timer, makes it easier to coordinate with dissimilar relay systems of different technology or manufacturer.

A <u>directional start</u> scheme uses only reverse directionally controlled distance elements and/or directionally supervised ground overcurrent elements to start blocking and forward looking elements to trip. As such, the relay will not start carrier unless it detects a reverse fault. Using this approach the local relay never sends a block signal (like the initial carrier signal blip) so that when a block signal is first received at the remote relay it is assumed, with confidence, that that the fault is external.

When selecting the use of non-directional or directional starting there are two key considerations:

- 1. When using non-directional starting how long is the initial carrier blocking signal pulse and what tripping delay it will cause. This delay is usually the time it takes for forward pilot elements to operate and STOP the blocking channel and any logic timers that may be included.
- 2. When using reverse direction starting how long does it take the reverse starting elements to operate and START the carrier blocking signal.

If the communication system is properly applied and maintained and there is no need for blocking extension timers to fill carrier holes then one only has to review the logic to determine the advantage of directional or non-directional starting for a properly operating DCB scheme. Consider non-directional starting and the logic of Figure 3. For remote external faults a blocking is received fast and is sustained at the local end. For an internal fault a blocking signal pulse is received. At the dropout of the pulse the carrier coordination timer starts. Therefore tripping will be delayed by the length of the pulse (pickup time of remote end FP units after non-directional start and channel time) plus coordination time. For directional starting using the logic of Figure 3 a blocking is received for remote external faults a bit slower at the local end than if non-directional starting were used – by the difference in the pickup of 50 (or change detector) and RP units at the remote end. For internal faults no blocking signal is received and tripping is delayed only by the coordination timer, which is usually set longer by the difference in 50 (or change detector) and RP operating times mentioned above. To provide appropriate security a directional start scheme requires increasing the set time of the coordination timer over that of a non-directional start scheme. This apparently slows the pilot tripping below that of a non-directional scheme, but does it really when the dropout time of the blocking signal pulse is considered part of the tripping delay with the coordination time for the non-directional start scheme. Therefore the choice of directional or nondirectional starting is probably a wash with the logic of Figure 3. Also, security for carrier holes is inherently provided up to the coordination time.

Now consider the logic of Figure 9. Initially we will assume no carrier holes and that the blocking signal extension timer is set to zero. For remote external faults a blocking is received fast with nondirectional starting and is sustained at the local end. For an internal fault a blocking signal pulse is received. The carrier coordination timer, however, starts with the operation of the FP trip units. If the non-directional blocking pulse is shorter than the coordination time then there is no tripping delay beyond the coordination time. For directional starting a blocking is received for remote external faults a bit slower at the local end than if non-directional starting were used – by the difference in the pickup of 50 (or change detector) and FP units at the remote end. For internal faults no blocking signal is received and tripping is delayed only by the coordination time which is usually set longer by the difference in 50 (or change detector) and RP units' operating times. For this case one may argue that the non-directional start is more secure – getting the block signal out faster – allowing a smaller coordinating time, and dependable fast pilot tripping is possible with the shorter coordination time. Security for carrier holes may be provided with the blocking signal extension timer. However, if using non-directional starting you will always get the start pulse and trip time will be delayed if set up close to or higher than the coordination time. Generally, the maximum blocking extension timer setting will be 0.5 to 0.75 times the coordination time for nondirectional starting to have an advantage in tripping speed over directional starting schemes.

Carrier Hole Mitigation

The first consideration is how we address carrier holes. As previously shown carrier holes are typically short, but can be several cycles or longer. Do we do preventative maintenance and prevent them from happening in the first place? Do we allow carrier hole misoperations to occur and then go do the appropriate corrective maintenance? Do we mask the holes, and if so, how long of a hole do we mask? How do we alarm them? The direction can be strongly debated and it is not our purpose to enter into it, but offer analysis and improvements to address carrier holes within DCB schemes. It is recommended however to detect and alarm for carrier holes either by logic or careful review of fault records.

When carrier holes are addressed and the block extension timer is used one must consider the effect of non-directional starting on the scheme. Consider that there is an internal fault and the local relay sends the fast non-directional start pulse. The remote relay will delay pilot tripping for internal faults until both the coordination and block extension timers have expired. For example, if a 1.0 cycle block extension timer is used, the relay will be blocked from tripping until 1.0 cycle after the carrier blocking signal has dropped out. Depending on the coordination timer setting (Figures 3 and 9) the block extension timer will provide additional tripping delay. As such, in the non-directional start scheme there are two competing goals when setting the block extension timer. First, a longer block extension timer will ride through longer holes in the carrier signal. Second, a longer block extension timer will delay pilot tripping because it will always get picked up by the initial carrier blocking signal pulse that always accompanies a non-directional start scheme. There are at least two ways to address this. The first is to simply use directional starting of the blocking signal and the second is to use logic that will not implement the longer block extension timer for a time (e.g. two cycles) after initial receipt of the blocking signal. Each will be discussed.

Increase Security with Directional Start

By using a directional start scheme much longer block extension timers can be used increasing security. In a directional start scheme only reverse directionally controlled ground overcurrent and/or impedance elements are used to start blocking. As such, the relay will not start carrier unless it detects a reverse fault. Using this approach the local relay never sends that initial blip of carrier so that when a block signal is first received at the remote relay it is assumed with confidence that that the fault is external. Therefore, much longer block extension delays (2-3 cycles) can be used without impacting fault clearing for internal faults.

Increase Security with a Block Signal Extension Implementation Delay

Experience has shown that DCB scheme misoperations due to carrier holes usually occur after two cycles into the fault. Again, this is usually due to transients generated by remote line breaker clearing. The philosophy here is to allow high speed tripping for a set time – two or more cycles - and then, if tripping has not occurred and the blocking signal is still being received, an external fault is assumed and the block extension timer is employed to handle holes that may occur during remote line clearing. Example logic is shown in Figure 11.



Figure 11. Block signal extension implementation delay – Y_s – an optional very short block extension delay, D – delay time to implementation of a larger block signal extension delay, Y_L

Blocking Start Signal Continuation

The blocking start signal continuation timer shown in Figure 10(a) provides immunity to issues of current reversals or other external fault clearing transients by assuring that the BLOCK signal received at the remote end is maintained long enough after the local RP units dropout so that the "already" operated remote FP units have time to dropout. Also, local end tripping is blocked to prevent tripping with fast operating FP units with short coordination times during current reversals (sometimes called transient blocking).

Open Terminal Start Inhibit

A transmission line may have an open terminal (open breaker(s) or line disconnect) while being energized or operated. Since the relay at that terminal cannot see a forward or reverse fault it is generally recommended that the open terminal condition block the operation of the channel blocking signal start function. This is shown in Figure 10(a). This allows the remote terminal to DCB pilot trip after the expiration of its coordination time. There are application exceptions that involve transformers with ground paths. One will be discussed later.

Channel Stopping

To maintain dependable "fast" tripping it is essential to STOP the channel blocking signal when forward faults are detected to allow the remote terminal to trip fast. Keep in mind that removal of the "start" signal into the PLC does not equal a "stop" into the PLC. There may be ring-down of the transmitter or receiver circuits, or additional functions starting carrier such as checkback. Ordinarily it is preferred that when the FP units operate that the stop function is asserted immediately without any interposing coordination time delay as shown in Figures 3, 9 and 10(b), but not as in Figure 12.

Consider that there is an external fault on a parallel line and the local end of the non-faulted line has initiated a non-directional start blocking signal to the remote end and sees the fault forward. At the remote end of the non-faulted line a reverse fault is seen and a block signal is sent to the local end. Everything is fine. Both ends of the non-faulted line are sending a blocking signal. Now consider that the parallel line fault evolves to the previously non-faulted line and both ends now see the fault forward. The coordination time must then expire before stopping the channel blocking signal that is being transmitted to the remote end. At the remote end the blocking signal extension timer must then expire before the remote end is allowed to trip. In this case there is an unnecessary tripping delay. The delay is better illustrated in Figure 13 where the coordination time, T_{CRD} , is 1.0 cycle, the blocking signal extension timer, T_{EXT} , is 0.75 cycle and there is a STOP signal execution time, an output contact time and a channel time delay totaling D, 0.25 cycle. These numbers are chosen to better illustrate the effect of the STOP signal logic location and the delay timers. It is also assumed that the BLOCK signal is initially being transmitted and received at both ends and the forward pilot tripping units, FP, at both ends operate simultaneously.



Figure 12. Basic Trip Logic with stop channel applied coordination time



Figure 13. Comparison of logic STOP signal assertion point – before and after coordination timer

In Case 1 Figure 9 logic is used and the STOP signal is asserted prior to the coordination timer and hence we are just waiting for the local coordination timer, T_{CRD} , to expire and the BLOCK signal from the remote end to dropout. Simultaneously at the remote end the block signal is stopped (STOP) and locally we must wait for the channel time, D, and the local blocking signal extension timer, T_{EXT} , to expire for a TRIP. The two actions, expirations of T_{CRD} and $D+T_{EXT}$, occur simultaneously (in parallel). If $D+T_{EXT}$ is less than T_{CRD} then there is no tripping time delay beyond the set coordination time T_{CRD} .

In Case 2 Figure 12 logic is used and the STOP signal is asserted at both ends after the coordination timer, T_{CRD} . In this case, however, we are not only waiting for the local T_{CRD} to expire for tripping, but we are also waiting for the remote end's T_{CRD} to expire and STOP the transmission of the block signal. The remote end's block signal is stopped after T_{CRD} and locally we must wait for the remote end's T_{CRD} plus the channel time, D, and the local blocking signal extension timer, T_{EXT} , to expire for a TRIP to occur. The two actions, expirations of T_{CRD} and D+T_{EXT}, occur sequentially (in series) and tripping will be delayed beyond T_{CRD} by D+T_{EXT}.

The application of Figure 12 logic can be slightly improved at one end by using reverse directional starting only, particularly if the signal extension timer is long. One line end will generally see the fault initially reverse sending a blocking signal and the other line end will not. When the fault

evolves to a forward fault the line end, say the remote end, where the blocking is not received trip will occur after its set coordination time. The local end trip will still be delayed beyond its set coordination time by the remote end's coordination time (to stop the blocking signal) and the block signal extension time.

A general rule that should be applied is to avoid local tripping logic that depends on remote relay time delays and if such is applied, study it carefully.

Channel Stopping with TRIP

Another common feature in digital relays is to stop the carrier blocking signal whenever the local relay declares a "TRIP" condition. This is generally appropriate as long as the element initiating the trip is a forward direct tripping element (Zone 1, high set 50N, pilot, etc.). However, if the trip is initiated by a reverse looking backup element ... reverse zone-3, local breaker failure etc., then the carrier blocking signal to the remote end may be prematurely stopped before the reverse fault is cleared by the local breaker. The breaker opening time is generally 2-3 cycles after the assertion of trip in the relay for newer gas breakers, but can be longer for older technology. Often this can be overcome with a channel continuation timer. It would, however, be more prudent to use only those high-speed forward trip elements to stop the carrier blocking signal and avoid using "any trip" to stop the blocking signal.

Other Application Considerations

67NF Delay Timer

If a ground-distance element is applied it is set overreaching just as the phase-distance element. It covers the vast majority of system ground faults where fault resistance is not excessive. The benefit of its use is that it does not detect faults beyond its reach setting, which usually reaches just beyond the remote bus. The 67NF when set sensitively, on the other hand, may reach to Timbuktu – many busses away. A long time delay for a sensitive directional ground tripping element (67NF) is therefore often used when applied with a forward ground distance tripping element (21NF) in a DCB scheme. For secure tripping it is desired to allow the 21NF to operate high speed with time delayed tripping of the 67NF. This is to insure that for a channel blocking signal failure [or carrier unintentionally left off] the exposure to overreach tripping is limited. The 67NF time delay is generally set to a time that allows remote line clearing of external faults beyond the reach of 21NF (e.g. 8 cycles). With this time delay the 67NF still provides good coverage for high-resistive internal faults with increased security against tripping for remote faults.

Non-directional start and reverse directional unit mis-coordination

As is typical in protective relaying there are tradeoffs and specifics of unique cases that may dictate the course of action. The following example discusses such a situation. A transmission line with a large ground path (source) on one end as shown in Figure 14 and is protected with a non-directional start DCB scheme. The non-directional starting unit is a low set 50N (3I0) function and the forward unit is a 67QF (3I0 overcurrent torque controlled with negative sequence directional element). When an internal fault occurs 50N operates starting a blocking signal, however, the 67QF function does not operate to STOP the blocking as expected because there is no I2 current available

for the directional unit to operate. The block signal started by the 50N is maintained thus requiring backup time delayed tripping in Relay B.



Figure 14. Line with dangling ground path

There are two ways to improve this scheme. The first is to use only directional start and thus not require any coordination. If the 67QF relay does not operate there is no block signal and the relay at Bus B will trip. However, there will be no tripping at Bus A with a negative sequence relay so the 67NF, which can see the fault, is preferred. The second method is to use a non-directional start 50N function and a 67NF (310 torque controlled with zero sequence directional element) function to assure tripping at both ends. This illustrates the importance to coordinate the start and tripping units operating characteristics to assure that they both will operate. Similarly, it is prudent to use coordinated start and directional blocking relays on tapped transformers that feed radial load (that are ground paths for transmission line faults) so the relay won't send blocking unless the fault is on the load side of the bank.

Weak-End Infeed

The configuration of Figure 14 discussed above subtly introduced the subject of weak-end infeed. The weak end can see reverse faults to start the carrier blocking signal to block the strong terminal. It, however, cannot see forward faults and cannot trip with its forward directional protection elements. Since the strong end trips for a forward fault when no blocking signal is received from the weak end, clearing internal faults from the strong end will occur. There is, however, still the issue that weak end tripping, if it is desired, will not occur unless weak-end infeed trip logic is provided. The problem with such logic <u>in a DCB scheme</u> is that there is never a positive indication the remote strong terminal sees a forward fault. Therefore, a non-permissive (no permission from the remote terminals) weak end infeed logic as in Figure 15 can be used. The timer should be set long to assure a persistent low phase voltage condition. Keep in mind also that there may be legitimate reasons not to trip the weak terminal.



Figure 15. A non-permissive weak end infeed logic – 27A, B, C – phase A, B, and C undervoltage. T – time delay for a weak-end infeed trip.

Binary Voltage Input Debounce Time

When the BLOCK signal is input into the relay through a dc voltage input there is usually a signal discriminator or a debounce timer that assures that the voltage input is not transient noise. Generally the input delay time is very small and can be neglected. It may be that the protection includes individually settable voltage input and contact output pickup and dropout delays. These settings may be used to provide coordination delay or blocking extension times. A review of these timer settings and how they affect overall performance of the DCB scheme is required.

Redundant Schemes

Finally, you must consider the overall line protection. If your DCB scheme is running in parallel with a highly reliable current differential scheme, for example, you can use longer coordination and block extension time delays to increase security of the overall scheme – without much negative impact on speed and dependability.

Conclusions

We have discussed many practical aspects of directional comparison blocking schemes; its basic implementation with PLC, the pros and cons of non-directional vs. directional starting, coordination time of blocking signal and FP tripping elements, carrier holes, and as well a few of the multitude of implementations seen in practice. We have shown the complexities and necessary considerations for the implementation of a seemingly rather simple, and often taken for granted, DCB scheme. Our intent was not simply to inform the reader but also to motivate the reader to vigorously investigate and "what if" the schemes at use in their utility. Just because "we've always done it this way" isn't a sound basis for how we should proceed in the future with new technology and more flexible protection systems. At the same time, changing just for the sake of change may open a can of worms that the casual user did not anticipate. There is no substitute for careful study and real world experience garnered through event analysis and study.

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