1. Introduction

Unit protection schemes, formed by a number of relays located remotely from each other, and some distance protection schemes, require some form of communication between each location in order to achieve a unit protection function. This form of communication is known as protection signalling. Additionally, communications facilities are also required when remote operation of a circuit breaker is required as a result of a local event. This form of communications is known as intertripping.

The communication messages involved may be quite simple, involving instructions for the receiving device to take some defined action (trip, block, etc.), or it may be the passing of measured data in some form from one device to another (as in a unit protection scheme).

Various types of communication links are available for protection signalling, for example:

- a. private pilot wires installed by the power authority
- b. pilot wires or channels rented from a communications company
- c. carrier channels at high frequencies over the power lines
- d. radio channels at very high or ultra high frequencies
- e. optical fibres

Whether or not a particular link is used depends on factors such as the availability of an appropriate communication network, the distance between protection relaying points, the terrain over which the power network is constructed, as well as cost.

Protection signalling is used to implement Unit Protection schemes, provide teleprotection commands, or implement intertripping between circuit breakers.

2. Unit protection schemes

Phase comparison and current differential schemes use signalling to convey information concerning the relaying quantity - phase angle of current and phase and magnitude of current respectively - between local and remote relaying points. Comparison of local and remote signals provides the basis for both fault detection and discrimination of the schemes.

Details of Unit Protection schemes are given in Chapter [C1: Overcurrent Protection for Phase and Earth Faults].

Communications methods are covered later in this Chapter.

3. Teleprotection commands

Some Distance Protection schemes described in Chapter [C4: Distance Protection Schemes] use signalling to convey a command between local and remote relaying points. Receipt of the information is used to aid or speed up clearance of faults within a protected zone or to prevent tripping from faults outside a protected zone.

Teleprotection systems are often referred to by their mode of operation, or the role of the teleprotection command in the system.
Intertripping is the controlled tripping of a circuit breaker so as to complete the isolation of a circuit or piece of apparatus in sympathy with the tripping of other circuit breakers. The main use of such schemes is to ensure that protection at both ends of a faulted circuit will operate to isolate the equipment concerned. Possible circumstances when it may be used are:

a. a feeder with a weak infeed at one end, insufficient to operate the protection for all faults

b. feeder protection applied to transformer-feeder circuits. Faults on the transformer windings may operate the transformer protection but not the feeder protection. Similarly, some earth faults may not be detected due to transformer connections

c. faults between the CB and feeder protection CTs, when these are located on the feeder side of the CB. Bus-zone protection does not result in fault clearance – the fault is still fed from the remote end of the feeder, while feeder unit protection may not operate as the fault is outside the protected zone.

d. some distance protection schemes use intertripping to improve fault clearance times for some kinds of fault – see Chapters [C4: Distance Protection Schemes] and [C5: Protection of Complex Transmission Circuits].

Intertripping schemes use signalling to convey a trip command to remote circuit breakers to isolate circuits. For high reliability EHV protection schemes, intertripping may be used to give back-up to main protections, or back-tripping in the case of breaker failure. Three types of intertripping are commonly encountered, and are described below.

![Diagram of intertripping](image)

**Figure D2.1:** Application of protection signalling and its relationship to other systems using communication (shown as a unidirectional system for simplicity)
4. Intertripping

4.1 Direct tripping
In direct tripping applications, intertrip signals are sent directly to the master trip relay. Receipt of the command causes circuit breaker operation. The method of communication must be reliable and secure because any signal detected at the receiving end will cause a trip of the circuit at that end. The communications system design must be such that interference on the communication circuit does not cause spurious trips. Should a spurious trip occur, considerable unnecessary isolation of the primary system might result, which is at best undesirable and at worst quite unacceptable.

4.2 Permissive tripping
Permissive trip commands are always monitored by a protection relay. The circuit breaker is tripped when receipt of the command coincides with operation of the protection relay at the receiving end responding to a system fault. Requirements for the communications channel are less onerous than for direct tripping schemes, since receipt of an incorrect signal must coincide with operation of the receiving end protection for a trip operation to take place. The intention of these schemes is to speed up tripping for faults occurring within the protected zone.

4.3 Blocking scheme
Blocking commands are initiated by a protection element that detects faults external to the protected zone. Detection of an external fault at the local end of a protected circuit results in a blocking signal being transmitted to the remote end. At the remote end, receipt of the blocking signal prevents the remote end protection operating if it had detected the external fault. Loss of the communications channel is less serious for this scheme than in others as loss of the channel does not result in a failure to trip when required. However, the risk of a spurious trip is higher.

Figure D2.1 shows the typical applications of protection signalling and their relationship to other signalling systems commonly required for control and management of a power system. Of course, not all of the protection signals shown will be required in any particular scheme.

5. Performance requirements

Overall fault clearance time is the sum of:

a. signalling time
b. protection relay operating time
c. trip relay operating time
d. circuit breaker operating time

The overall time must be less than the maximum time for which a fault can remain on the system for minimum plant damage, loss of stability, etc. Fast operation is therefore a pre-requisite of most signalling systems.

Typically the time allowed for the transfer of a command is of the same order as the operating time of the associated protection relays. Typical operating times range from 5 to 40ms dependent on the mode of operation of the teleprotection system.

Protection signals are subjected to the noise and interference associated with each communication medium. If noise reproduces the signal used to convey the command, unwanted commands may be produced, whilst if noise occurs when a command signal is being transmitted, the command may be retarded or missed completely. Performance is expressed in terms of security and dependability. Security is assessed by the probability of an unwanted command occurring, and dependability is assessed by the probability of missing a command. The required degree of security and dependability is related to the mode of operation, the characteristics of the communication medium and the operating standards of the particular power authority.

Typical design objectives for teleprotection systems are not more than one incorrect trip per 500 equipment years and less than one failure to trip in every 1000 attempts, or a delay of more than 50msec should not occur more than once per 10 equipment years. To achieve these objectives, special emphasis may be attached to the security and dependability of the teleprotection command for each mode of operation in the system, as follows.

5.1 Performance requirements - Intertripping
Since any unwanted command causes incorrect tripping, very high security is required at all noise levels up to the maximum that might ever be encountered.
5. Performance requirements

5.2 Performance requirements - Permissive tripping

Security somewhat lower than that required for intertripping is usually satisfactory, since incorrect tripping can occur only if an unwanted command happens to coincide with operation of the protection relay for an out-of-zone fault.

For permissive over-reach schemes, resetting after a command should be highly dependable to avoid any chance of maloperations during current reversals.

5.3 Performance requirements - Blocking schemes

Low security is usually adequate since an unwanted command can never cause an incorrect trip. High dependability is required since absence of the command could cause incorrect tripping if the protection relay operates for an out-of-zone fault.

Typical performance requirements are shown in Figure D2.2.

6. Transmission media, interference and noise

The transmission media that provide the communication links involved in protection signalling are:

a. private pilots
b. rented pilots or channels
c. power line carrier
d. radio
e. optical fibres

Historically, pilot wires and channels (discontinuous pilot wires with isolation transformers or repeaters along the route between signalling points) have been the most widely used due to their availability, followed by Power Line Carrier Communications (PLCC) techniques and radio. In recent years, fibre-optic systems have become the usual choice for new installations, primarily due to their complete immunity from electrical interference. The use of fibre-optic cables also greatly increases the number of communication channels available for each physical fibre connection and thus enables more comprehensive protection and monitoring of the power system to be achieved by the provision of a large number of communication channels.

6.1 Private pilot wires and channels

Pilot wires are continuous copper connections between signalling stations, while pilot channels are discontinuous pilot wires with isolation transformers or repeaters along the route between signalling stations. They may be laid in a trench with high voltage cables, laid by a separate route or strung as an open wire on a separate wood pole route.

Distances over which signalling is required vary considerably. At one end of the scale, the distance may be only a few tens of metres, where the devices concerned are located in the same substation. For applications on EHV lines, the distance between devices may be between 10-100km or more. For short distances, no special measures are required against interference, but over longer distances, special send and receive relays may be required to boost signal levels and provide immunity against induced voltages from power circuits, lightning strikes to ground adjacent to the route, etc. Isolation transformers may also have to be provided to guard against rises in substation ground potential due to earth faults.
6. Transmission media, interference and noise

The capacity of a link can be increased if frequency division multiplexing techniques are used to run parallel signalling systems, but some Utilities prefer the link to be used only for protection signalling.

Private pilot wires or channels can be attractive to a Utility running a very dense power system with short distances between stations.

6.2 Rented pilot wires and channels

These are rented from national communication authorities and, apart from the connection from the relaying point to the nearest telephone exchange, the routing will be through cables forming part of the national communication network.

An economic decision has to be made between the use of private or rented pilots. If private pilots are used, the owner has complete control, but bears the cost of installation and maintenance. If rented pilots are used, most of these costs are eliminated, but fees must be paid to the owner of the pilots and the signal path may be changed without warning. This may be a problem in protection applications where signal transmission times are critical.

The chance of voltages being induced in rented pilots is smaller than for private pilots, as the pilot route is normally not related to the route of the power line with which it is associated. However, some degree of security and protection against induced voltages must be built into signalling systems.

Electrical interference from other signalling systems, particularly 17, 25 and 50Hz ringing tones up to 150V peak, and from noise generated within the equipment used in the communication network, is a common hazard. Similarly, the signalling system must also be proof against intermittent short and open circuits on the pilot link, incorrect connection of 50 volts d.c. across the pilot link and other similar faults.

Station earth potential rise is a significant factor to be taken into account and isolation must be provided to protect both the personnel and equipment of the communication authority.

The most significant hazard to be withstood by a protection signalling system using this medium arises when a linesman inadvertently connects a low impedance test oscillator across the pilot link that can generate signalling tones. Transmissions by such an oscillator may simulate the operating code or tone sequence that, in the case of direct intertripping schemes, would result in incorrect operation of the circuit breaker.

Communication between relaying points may be over a two-wire or four-wire link. Consequently the effect of a particular human action, for example an incorrect disconnection, may disrupt communication in one direction or both.

The signals transmitted must be limited in both level and bandwidth to avoid interference with other signalling systems. The owner of the pilots will impose standards in this respect that may limit transmission capacity and/or transmission distance.

With a power system operating at, say, 132kV, where relatively long protection signalling times are acceptable, signalling has been achieved above speech together with metering and control signalling on an established control network. Consequently the protection signalling was achieved at very low cost. High voltage systems (220kV and above) have demanded shorter operating times and improved security, which has led to the renting of pilot links exclusively for protection signalling purposes.

6.3 Power line carrier communications techniques

Where long line sections are involved, or if the route involves installation difficulties, the expense of providing physical pilot connections or operational restrictions associated with the route length require that other means of providing signalling facilities are required.

Power Line Carrier Communications (PLCC) is a technique that involves high frequency signal transmission along the overhead power line. It is robust and therefore reliable, constituting a low loss transmission path that is fully controlled by the Utility.

High voltage capacitors are used, along with drainage coils, for the purpose of injecting the signal to and extracting it from the line. Injection can be carried out by impressing the carrier signal voltage between one conductor and earth or between any two phase conductors. The basic units can be built up into a high pass or band pass filter as shown in Figure D2.3.

The high voltage capacitor is tuned by a tuning coil to present a low impedance at the signal frequency; the parallel circuit presents a high impedance at the signal frequency while providing a path for the power frequency currents passed by the capacitor.

The complete arrangement is designed as a balanced or unbalanced half-section band pass filter, according to whether the transmission is phase-phase or phase-earth; the power line characteristic impedance, between 400 and 600 ohms, determines the design impedance of the filter.

It is necessary to minimise the loss of signal into other parts of the power system, to allow the same frequency to be used on another line. This is done with a ‘line trap’ or ‘wave trap’, which in its simplest form is a parallel circuit tuned to present a very high impedance to the signal frequency. It is connected in the phase conductor on the station side of the injection equipment. The complete carrier coupling equipment is shown in Figure D2.4.

The single frequency line trap may be treated as an integral part of the complete injection equipment to accommodate two or more carrier systems. However, difficulties may arise in an overall design, as, at certain frequencies, the actual station reactance, which is normally capacitive, will tune with
6. Transmission media, interference and noise

The trap, which is inductive below its resonant frequency; the result will be a low impedance across the transmission path, preventing operation at these frequencies. This situation can be avoided by the use of an independent ‘double frequency’ or ‘broad-band’ trap.

The coupling filter and the carrier equipment are connected by high frequency cable of preferred characteristic impedance 75 ohms. A matching transformer is incorporated in the line coupling filter to match it to the HF (High Frequency) cable. Surge diverters are fitted to protect the components against transient overvoltages.

The attenuation of a channel is of prime importance in the application of carrier signalling, because it determines the amount of transmitted energy available at the receiving end to overcome noise and interfering voltages. The loss of each line terminal will be 1 to 2dB through the coupling filter, a maximum of 3dB through its broad-band trap and not more than 0.5dB per 100 metres through the high frequency cable.

An installation of PLCC equipment including capacitor voltage transformers and line traps, in a line-to-line injection arrangement, is shown in Figure D2.4.

Figure D2.3: Typical phase-to-phase coupling equipment

Figure D2.4: Carrier coupling equipment
The high frequency transmission characteristics of power circuits are good, with losses amounting to 0.02 to 0.2dB per kilometre depending upon line voltage and frequency. Line attenuation is not affected appreciably by rain, but serious increase in loss may occur when the phase conductors are thickly coated with hoar-frost or ice. Attenuations of up to three times the fair weather value have been experienced. Receiving equipment commonly incorporates automatic gain control (AGC) to compensate for variations in attenuation of signals.

High noise levels arise from lightning strikes and system fault inception or clearance. Although these are of short duration, lasting only a few milliseconds at the most, they may cause overloading of power line carrier receiving equipment. Signalling systems used for intertripping in particular must incorporate appropriate security features to avoid maloperation. The most severe noise levels are encountered with operation of the line isolators, and these may last for some seconds. Although maloperation of the associated teleprotection scheme may have little operational significance, since the circuit breaker at one end at least is normally already open, high security is generally required to cater for noise coupled between parallel lines or passed through line traps from adjacent lines.

Signalling for permissive intertrip applications needs special consideration, as this involves signalling through a power system fault. The increase in channel attenuation due to the fault varies according to the type of fault, but most power authorities select a nominal value, usually between 20 and 30dB, as an application guide. A protection signal boost facility can be employed to cater for an increase in attenuation of this order of magnitude, to maintain an acceptable signal-to-noise ratio at the receiving end, so that the performance of the service is not impaired.

Most direct intertrip applications require signalling over a healthy power system, so boosting is not normally needed. In fact, if a voice frequency intertrip system is operating over a carrier bearer channel, the dynamic operating range of the receiver must be increased to accommodate a boosted signal. This makes it less inherently secure in the presence of noise during a quiescent signalling condition.

6.4 Radio channels

At first consideration, the wide bandwidth associated with radio frequency transmissions could allow the use of modems operating at very high data rates. Protection signalling commands could be sent by serial coded messages of sufficient length and complexity to give high security, but still achieve fast operating times. In practice, it is seldom economic to provide radio equipment exclusively for protection signalling, so standard general-purpose telecommunications channel equipment is normally adopted.

Typical radio bearer equipment operates at the microwave frequencies of 0.2 to 10GHz. Because of the relatively short range and directional nature of the transmitter and receiver aerial systems at these frequencies, large bandwidths can be allocated without much chance of mutual interference with other systems.

Multiplexing techniques allow a number of channels to share the common bearer medium and exploit the large bandwidth. In addition to voice frequency channels, wider bandwidth channels or data channels may be available, dependent on the particular system. For instance, in analogue systems using frequency division multiplexing, normally up to 12 voice frequency channels are grouped together in basebands at 12-60kHz or 60-108kHz, but alternatively the baseband may be used as a 48kHz signal channel. Modern digital systems employing pulse code modulation and time division multiplexing usually provide the voice frequency channels by sampling at 8kHz and quantising to 8 bits; alternatively, access may be available for data at 64kbits/s (equivalent to one voice frequency channel) or higher data rates.

Radio systems are well suited to the bulk transmission of information between control centres and are widely used for this. When the route of the trunk data network coincides with that of transmission lines, channels can often be allocated for protection signalling. More generally, radio communication is between major stations rather than the ends of individual lines, because of the need for line-of-sight operation between aerials and other requirements of the network. Roundabout routes involving repeater stations and the addition of pilot channels to interconnect the radio installation and the relay station may be possible, but overall dependability will normally be much lower than for PLCC systems in which the communication is direct from one end of the line to the other.

Radio channels are not affected by increased attenuation due to power system faults, but fading has to be taken into account when the signal-to-noise ratio of a particular installation is being considered.

Most of the noise in such a protection signalling system will be generated within the radio equipment itself. A polluted atmosphere can cause radio beam refraction that will interfere with efficient signalling. The height of aerial tower should be limited, so that winds and temperature changes have the minimum effect on their position.

6.5 Optical fibre channels

Optical fibres are fine strands of glass, which behave as wave guides for light. This ability to transmit light over considerable distances can be used to provide optical communication links with enormous information carrying capacity and an inherent immunity to electromagnetic interference.

A practical optical cable consists of a central optical fibre which comprises core, cladding and protective buffer coating surrounded by a protective plastic overshield containing strength members which, in some cases, are enclosed by a layer of armouring.
To communicate information a beam of light is modulated in accordance with the signal to be transmitted. This modulated beam travels along the optical fibre and is subsequently decoded at the remote terminal into the received signal. On/off modulation of the light source is normally preferred to linear modulation since the distortion caused by non-linearities in the light source and detectors, as well as variations in received light power, are largely avoided.

The light transmitter and receiver are usually laser or LED devices capable of emitting and detecting narrow beams of light at selected frequencies in the low attenuation 850, 1300 and 1550 nanometre spectral windows. The distance over which effective communications can be established depends on the attenuation and dispersion of the communication link and this depends on the type and quality of the fibre and the wavelength of the optical source. Within the fibre there are many modes of propagation with different optical paths that cause dispersion of the light signal and result in pulse broadening.

The degrading of the signal in this way can be reduced by the use of ‘graded index’ fibres that cause the various modes to follow nearly equal paths. The distance over which signals can be transmitted is significantly increased by the use of ‘monomode’ fibres that support only one mode of propagation.

With optical fibre channels, communication at data rates of hundreds of megahertz is achievable over a few tens of kilometres, whilst greater distances require the use of repeaters. An optical fibre can be used as a dedicated link between two terminal equipments, or as a multiplexed link that carries all communication traffic such as voice, telecontrol and protection signalling. In the latter case the available bandwidth of a link is divided by means of time division multiplexing (T.D.M.) techniques into a number of channels, each of 64kbits/s (equivalent to one voice frequency channel which typically uses an 8-bit analogue-to-digital conversion at a sampling rate of 8kHz). A number of Utilities sell surplus capacity on their links to telecommunications operators. The trend of using rented pilot circuits is therefore being reversed, with the Utilities moving back towards ownership of the communication circuits that carry protection signalling.

The equipments that carry out this multiplexing at each end of a line are known as ‘Pulse Code Modulation’ (P.C.M.) terminal equipments. This approach is the one adopted by telecommunications authorities and some Utilities favour its adoption on their private systems, for economic considerations.

Optical fibre communications are well established in the electrical supply industry. They are the preferred means for the communications link between a substation and a telephone exchange when rented circuits are used, as trials have shown that this link is particularly susceptible to interference from power system faults if copper conductors are used. Whilst such fibres can be laid in cable trenches, there is a strong trend to associate them with the conductors themselves by producing composite cables comprising optical fibres embedded within the conductors, either earth or phase. For overhead lines use of OPGW (Optical Ground Wire) earth conductors is very common, while an alternative is to wrap the optical cable helically around a phase or earth conductor. This latter technique can be used without restringing of the line.
7. Signalling methods

Various methods are used in protection signalling; not all need be suited to every transmission medium. The methods to be considered briefly are:

a. D.C. voltage step or d.c. voltage reversals
b. plain tone keyed signals at high and voice frequencies
c. frequency shift keyed signals involving two or more tones at high and voice frequencies

General purpose telecommunications equipment operating over power line carrier, radio or optical fibre media incorporate frequency translating or multiplexing techniques to provide the user with standardised communication channels. They have a nominal bandwidth/channel of 4kHz and are often referred to as voice frequency (vf) channels. Protection signalling equipments operating at voice frequencies exploit the standardisation of the communication interface. Where voice frequency channels are not available or suitable, protection signalling may make use of a medium or specialised equipment dedicated entirely to the signalling requirements.

Figure D2.5 illustrates the communication arrangements commonly encountered in protection signalling.

7.1 D.C. voltage signalling

A d.c. voltage step or d.c. voltage reversals may be used to convey a signalling instruction between protection relaying points in a power system, but these are suited only to private pilot wires, where low speed signalling is acceptable, with its inherent security.
7. Signalling methods

7.2 Plain tone signals

Plain high frequency signals can be used successfully for the signalling of blocking information over a power line. A normally quiescent power line carrier equipment can be dedicated entirely to the transfer to teleprotection blocking commands. Phase comparison power line carrier unit protection schemes often use such equipment and take advantage of the very high speed and dependability of the signalling system. The special characteristics of dedicated ‘on/off’ keyed carrier systems are discussed later. A relatively insensitive receiver is used to discriminate against noise on an amplitude basis, and for some applications the security may be satisfactory for permissive tripping, particularly if the normal high-speed operation of about 6ms is sacrificed by the addition of delays. The need for regular reflex testing of a normally quiescent channel usually precludes any use for intertripping.

Plain tone power line carrier signalling systems are particularly suited to providing the blocking commands often associated with the protection of multi-ended feeders, as described in Chapter [C5: Protection of Complex Transmission Circuits]. A blocking command sent from one end can be received simultaneously at all the other ends using a single power line carrier channel. Other signalling systems usually require discrete communication channels between each of the ends or involve repeaters, leading to decreased dependability of the blocking command.

Plain voice frequency signals can be used for blocking, permissive intertrip and direct intertrip applications for all transmission media but operation is at such a low signal level that security from maloperation is not very good. Operation in the ‘tone on’ to ‘tone off’ mode gives the best channel monitoring, but offers little security; to obtain a satisfactory performance the output must be delayed. This results in relatively slow operation: 70 milliseconds for permissive intertripping, and 180 milliseconds for direct intertripping.

7.3 Frequency shift keyed signals

Frequency shift keyed high frequency signals can be used over a power line carrier link to give short operating times (15 milliseconds for blocking and permissive intertripping, 20 milliseconds for direct intertripping) for all applications of protection signalling. The required amount of security can be achieved by using a broadband noise detector to monitor the actual operational signalling equipment.

Frequency shift keyed voice frequency signals can be used for all protection signalling applications over all transmission media. Frequency modulation techniques make possible an improvement in performance, because amplitude limiting rejects the amplitude modulation component of noise, leaving only the phase modulation components to be detected.

The operational protection signal may consist of tone sequence codes with, say, three tones, or a multi-bit code using two discrete tones for successive bits, or of a single frequency shift.

Modern high-speed systems use multi-bit code or single frequency shift techniques. Complex codes are used to give the required degree of security in direct intertrip schemes; the short operating times needed may result in uneconomical use of the available voice frequency spectrum, particularly if the channel is not exclusively employed for protection signalling. As noise power is directly proportional to bandwidth, a large bandwidth causes an increase in the noise level admitted to the detector, making operation in the presence of noise more difficult. So, again, it is difficult to obtain both high dependability and high security.

The signal frequency shift technique has advantages where fast signalling is needed for blocked distance and permissive intertrip applications. It has little inherent security, but additional circuits responsive to every type of interference can give acceptable security. This system does not require a channel capable of high transmission rates, as the frequency changes once only; the bandwidth can therefore be narrower than in coded systems, giving better noise rejection as well as being advantageous if the channel is shared with telemetry and control signalling, which will inevitably be the case if a power line carrier bearer is employed.