13

PROTECTION SYSTEMS USING TELECOMMUNICATIONS

Working Group 05 of Study Committee 34 (Protection)

& 35 (Communication and Telecontrol)

Convener : L. LOHAGE

October 1987

cigré

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LIST OF CONTENTS

1. FOREWORD

CIGRÉ study committees 34 and 35 decided in 1982 to rewrite and modernize the CIGRÉ publication TELE PROTECTION. The new title is: PROTECTION SYSTEMS USING TELECOMMUNICATION. The report deals with protection systems rather than with protection equipments or relay units.

A working group was set up with the following members.

J Ferrer	Spain
H Hupfauer	Germany
L Lohage	Sweden, overall convener
C Magnus	Norway, comm. convener
V Narayan	Switzerland
C Starace	Italy

2. SCOPE AND OBJECT

Telecommunication connected to or included in protection systems seems to be more common when transmission power systems are extended and developed.

The increasing integration of telecommunication in the protection systems necessitates a good overall view of protection and telecommunication problems and of course power system problems as well.

This report contributes to and promotes mutual appreciation of the problems experienced by the telecommunication and protection engineers. It also presents the limitations as well as the capabilities of the protection and the telecommunication parts of the protection systems.

Only the most common protection systems are described. Protection systems for multiterminal and seriescompensated lines are not included.

The report is written on an educational level understandable for utility engineers with a few years' experience in the fields of protection or telecommunication.

3 TERMINOLOGY

3.1 General

The terminology used in this report is mainly based on IEC-documents. These words have been used for many years, so it is not advisable at this time to make too many changes in spite of the fact that some expressions can be difficult to understand. The report will in the following describe and clarify almost all words.

Words not defined by IEC but very often used have also been listed in this chapter. Sometimes more than one word is used for the same thing (synonyms). Only those words written as a heading are recommended for use.

Three expressions which are very seldom used at least by relay-engineers, have been introduced in this report. They are

- analogue protection system
- command protection system

The expression covering both of them is

- protection systems using telecommunication.

3.2 Definitions etc

ABC-breaker system

A switchyard arranged with one or two main busbars and one transfer bus. US = Main and transfer bus.

Absolutely selective protection system
Unit protection system

A protection system the operation and selectivity of which are solely dependent on the comparison of electrical quantities at each end of the protected section. (Compare with relatively selective protection)

Accelerated underreach distance protection system

A command protection system. An underreach distance protection system in which an overreach zone measurement is carried out without delay on the receipt of a signal from the remote end.

Analogue protection system

A protection system using telecommunication in which analogue power quantities are transmitted from one end of a power line by the telecommunication system either in analogue or digital form for comparison at the other end.

Example: phase comparison protection system, longitudinal differential protection system.

Arcing time

The interval of time between the instant of the first initiation of an arc and the instant of final arc extinction (e.g. within the circuit breaker)

Attenuation

The ratio, measured in dB, e.g. between the power which could be coupled to a line on its matching impedance and the power received at the output of the power line itself. Compare IEEE.

Automatic reclosing

An automatic control function which is designed to initiate the reclosing of a circuit-breaker after tripping due to a protection system operation.

Automatic restoration

Scheduled, sequentially and delayed automatic reconnection of circuit breakers or other specific switching devices. Automatic restoration could follow an unsuccessful automatic reclosing or a generalized disconnection condition with or without automatic reclosing operation and so on. Automatic restoration is normally programmed to voltage restore partially or whole station after a great disturbance occurrence.

Auto reclose open time

The time during the automatic reclosing cycle when the circuit breaker is open (compare with interruption time).

Availability

The probability of a device, an equipment or a system being able to perform correctly its required function, under stated conditions at a given instant when required. (See also reliability.) (When the time for maintainance is taken into consideration reliability is taken over by availability)

Back-up protection system

A protection system which is intended to operate when the main protection system or associated circuit breaker fails or is out of service.

Basic-time

The operating time for the instantaneous function of a protection system. Normally the first zone of a distance protection.

Baud

Measuring unit for modulation rate used in discrete modulation processes to indicate the maximum number of times per second the modulator may reach discrete modulation positions.

Blocking overreach distance protection system

A command protection system. An overreach distance protection system in which a signal is transmitted from one end following detection of a reverse external fault. Receipt of that signal at the other end blocks the local tripping initiated by overreaching distance protection.

Buchholz relay

A protective relay, responsive either to the collection of gas produced by incipient faults or to oil surges caused by explosive faults within a transformer tank, arranged to operate an alarm or to trip the transformer out of circuit.

Check line function

A function whereby the instantaneous zone of a protection system covers more than 100 % of the power line for a brief period following line energization. When the circuit breaker has been in the closed position for a few seconds the normal characteristic of the protection system is automatically switched in. Automatic reclosing is normally prevented during the check line function. US = Dead line pick-up function.

Check zone

Term applied to the non selective part of a multi-zone bus protection system, supervising current flow at the terminals of the complete station. Tripping is conditional on operation of both the check and a discriminative zone.

Circuit breaker failure protection system

A specific form of local backup protection which operates into the event of a circuit-breaker failing to clear a fault and trips all other circuits feeding into the same section of busbar as that circuit breaker.

Circuit breaker operating time

The time from the instant the circuit breaker receives a tripping impulse to the instant when main current through the circuit breaker has been interrupted.

Circuit local back-up protection

Back-up protection system energized from those instrument transformers which energize the main protection system or from instrument transformers associated with the same primary circuit as the main protection system.

Cladding

The material covering the core of a fibre optic cable. The cladding is intended to keep the light beam within the core and is not intended to transmit light. The cladding has therefore a lower refraction index than the core.

Command protection system

A protection system using telecommunication in which the command signal is transmitted by a telecommunication system to permissive trip or intertrip the circuit breaker for internal fault or block the protection equipment for external fault. US = pilot protection.

Correct fault clearance (clearing)

The clearance of a power system fault is defined as correct if it is achieved selectively and within the prescribed fault clearance time.

Cross - country fault

Simultaneous flashover to earth of two different phases in different line sections of the same power system generally, although not necessarily at the same voltage level.

Dead time

Dead interval. The time during an automatic reclosing cycle when no network voltage is applied to the power line conductors.

Deblocking overreach distance protection system

A command protection system. Protection system using telecommunication in which a received signal from the remote end of the line will override the blocking of an overreach distance protection.
US = Unblocking etc.

Decision time

The time needed at the receiver side of a teleprotection system from the beginning of the signal reception to the instant the output is activated. This time intends to prevent unwanted action and is spent on some kind of processing which may vary from simple integration to more complex digital decoding and processing.

Dedicated communication system

In the protection field it is understood that a separate telecommunication channel is used for protection purposes.

Dependability

The probability of not having a failure to trip operation (compare with security).

Differential current

The differential current in a differential circuit is the sum of currents coming into the protected area.

Digital protection

A static protection in which the characteristic response is developed by digital processing of the electrical input quantities.

Directional comparison protection system

A command protection system where the directions of current flow, using a locally derived voltage or current as a reference, are compared at each end of the protected section.

Distance protection system

A relatively selective protection system, the operation and selectivity of which depend on local measurement of parameters from which the equivalent distance to the fault is evaluated by comparing with zone settings.

Double fault

Simultaneous faults on two points on the network with the same geographical position. E.g. one fault on each circuit at a particular tower of a double circuit power line (compare with cross country fault).

Electromechanical protection

An electrical protection in which the designed response is developed by the relative movement of mechanical elements under the action of an input.

External fault

Fault outside the pre-established protected area (compare internal fault).

Failure to operate

Underfunction. The condition of a protection system which would have had to operate but which did not operate because of a technological failure or a design deficiency (compare with unwanted operation).

Fault clearance time
(clearing time)

The time interval between the instant of occurrence of a fault and the instant of the fault clearance by the automatic tripping of the appropriate circuit breakers. The fault clearance time is the sum of the protection-system-operating time and circuit-breaker-operating time.

Four corner system

Ring system switchyard layout normally having four circuits. (bays) US = Four corner ring bus system.

Frequency modulation (FM)

Variation of the frequency of the carrier signal in a modulation process according to the amplitude of the modulating signal.

Full scheme

Non-switched scheme. A distance protection with one measuring unit for each phase and each zone (compare with switched scheme).

Full wave phase comparison

A phase comparison protection system where the comparison is made twice per cycle. Comparison is made both on positive and negative half cycles (compare with half wave phase comparison).
US = Full wave dual phase comparison.

Half wave phase comparison

A phase comparison protection system where the comparison is made once a cycle in the positive or negative half cycle (compare full wave phase comparison).

High impedance scheme

Normally an absolutely selective protection. A current differential protection scheme in which the summation of current is presented to a high impedance voltage relay to detect an internal fault (compare low impedance).

High set

If e.g. two overcurrent relays are used as a part of a protection system one can be set on a high value (high set) and the other one on a low value (compare low set).

Incorrect operation

Maloperation. An unwanted or failure to trip operation.

Inrush current
A transient current associated with initial magnetizing of transformers. (cables, reactors etc)

Internal fault

Fault inside the pre-established protected area (compare with external fault.)

Interruption time

The time, during an automatic reclosing cycle, when the power flow is interrupted, taking into account all circuits breaker operations. (Compare with dead time)

Intertripping
Transfer tripping

The tripping of circuit breaker(s) by signals initiated from the protection at a remote location independent of the state of the protection at the local location. (Compare with underreach distance protection)
US = Direct trip

Load impedance

The ratio of phase voltage and phase current during power transmission assuming no shunt fault exists.

$$Z_L = \frac{U_L}{I_L} \quad US = U_L \longrightarrow V_L$$

Local back-up protection

A back-up protection system located in the same substation as the main protection (compare with circuit local back-up, substation local back-up and remote back-up).

Longitudinal differential protection system

An absolutely selective protection system. The operation and selectivity of which depend on the comparison of the phase and magnitude of the currents at the ends of the protected section.

Longitudinal differential protection system using pilot wire

A longitudinal differential protection system in which the communication system is a pilot wire.

Longitudinal differential protection system using modulation techniques

A longitudinal differential protection system using a telecommunication system in which the modulation technique used may be frequency modulation (FM) or pulse code modulation (PMC).

Low impedance scheme

Normally an absolutely selective protection system. Current relay is used as a differential relay in a differential protection (compare with high impedance scheme).

Low set

If e.g. two over current relays are used as part of a protection system, one can be set with a low value (low set) and the other one with high value (compare high set).

Main protection

A protection system expected to have priority over backup systems in initiating fault clearance.
US = primary protection.

Note: For a given installation, two or more main protection systems may be provided which may operate on either the same principle or different principles.

Mark signal

For a telecommunication system based on a two-condition modulation, the mark signal represents the condition in which the digit one is transmitted. In amplitude modulated systems this corresponds to tone-on condition while in frequency shift keying modulation systems this corresponds to the low frequency condition.

Mixing transformer

Summation transformer. An auxiliary transformer, which mixes the measured values from the three phases and reduces a single value output. The ratio between input and output is different for each phase. The mixing transformer is used in non-segregated analogue protection systems and may be additional to or included in the protection equipment (compare sequence network).

Negative sequence component

One of the symmetrical sequence components which can exist in an unsymmetrical three phase system.
US = Negative phase sequence comp.

$$I_2 = \frac{1}{3}(I_{L1} + a^2 I_{L2} + a I_{L3})$$

where a is 120° operator

Network fault (disturbance)

An unplanned condition on a network that is characterized by high current instability or significantly low frequency or significantly low voltage or high load current that requires corrective action to be taken.

Non-segregated protection system

A protection system using a mixing transformer or phase sequence network or other means to supply one protection equipment common for all three power phases.
US = Non-segregated mixed excitation protection system.

Non-system fault

An incident which results in the unwanted tripping of a circuit breaker as a result of a fault other than a power-system fault condition such as the unwanted operation of protection in the absence of a power system fault or the tripping of a circuit breaker due to some other secondary equipment failure or to human error.

One and a half circuit breaker system

A switchyard arranged with three circuit breakers per two circuits.(bays) US = Breaker - and - a - half

Overreaching

The condition of a distance protection system when the zone setting corresponds to a distance longer than the length of the protected circuit.

Peak envelope power of a radio transmitter

The average power supplied to the antenna or the transmission line by a transmitter during one radio-frequency cycle at the highest crest of the modulation envelope, taken under conditions of normal operation.

Permissive overreach distance protection system

A command protection system with overreach distance protection at each power line end. A signal is transmitted when a fault is detected by the overreaching distance protection. Receipt of the signal at the other end permits tripping if the local overreaching protection has operated to signify that the fault is internal.

Permissive protection system

A command protection system in which tripping on receipt of a signal is only allowed when the local protection also operates.

Permissive underreach distance protection system

A command protection system with underreach distance protection at each power line end. A signal is transmitted when a fault is detected by the underreaching distance protection. Receipt of the signal at the other end permits tripping if the local protection system has started.

Note: Sometimes measuring relays rather than distance zones (e.g. underimpedance or overcurrent or undervoltage fault detectors) are used as permissive criteria.

Phase comparison protection system

An absolutely selectively protection system where the operation and selectivity of which depend on the comparison of the phase angle of the currents at each end of the protected area.

Phase sequence mixing network

A circuit used to mix positive, negative and zero sequence quantities to produce a single output representative of all three phases. The proportions of positive, negative and zero sequence quantities used are chosen to suit the protection relay and its range of applications.

Positive sequence component

One of the symmetrical sequence components which exists in an unsymmetrical three phase system.
US = pos. phase sequence comp.

$$I_1 = \frac{1}{3}(I_{L1} + a\, I_{L2} + a^2\, I_{L3})$$

where a is the 120° operator

Note: The positive sequence component also exists in a symmetrical three phase system.

Power-system fault

An abnormality on the power-system which involves or is the result of failure of a primary-system circuit or item of primary system plant or equipment and which requires the disconnection of the faulted circuit, plant or equipment from the power system by the automatic tripping of the appropriate circuit breakers.

Note: Power system faults can be shunt faults or series faults (compare with non-power system fault).

Principle fault

Soft ware fault. A failure (unwanted or failure) of a protection system to function as required due to a planning or design defect, that may not be identified by test procedures (compare with spontaneous fault).

Propagation time

The time elapsed between the instant of application to a telecommunication system, under stated conditions, of a specific value of the transmitted signal and the instant when the received signal assumes the corresponding value at the input of the teleprotection receiver.

Protection

a) The provisions for detecting abnormal conditions in a power system and then initiating fault clearance or actuating signals or indications.

Example: The arrangements to be provided for protection of a 400 kV network.

b) A term designating the protection equipments or system intended to protect a plant item in a power system.

Example: Transformer protection, line protection, generator protection.

Protection equipment (protective equipment)

A group of several protection relays and/or logic elements installed to perform a specified function of protection which is defined by the adjective (prefix) represented by the dotted line.

Example: A distance protection equipment, a phase comparison protection equipment (the equipment installed at one end of a power line).

Protection relay (protective relay)

An electrical measuring relay which either solely or in combination with other electrical relays constitutes the protection equipment.

Protection system (protective system)

A complete arrangement of protection equipment and other devices required to achieve a specified function based on one protection principle.

Example: A phase comparison protection system, a differential protection system.

Note: a protection system is all embracing and includes not only the protection equipment(s) but also the necessary instruments, transformers, telecommunication links, tripping circuit, auxiliary supplies. Depending on the principle of the protection system, it may include one end or all the ends of the protected circuit and possibly automatic reclosing equipment.

Protection system operating time

The time interval between the instant that a power system fault causes a specific set of values of the input energizing quantities to be applied to the input of the protection system, including instrument transformers, and the instant when the output circuits send trip impulses to the circuit breaker.

Protection system using telecommunication

A protection system requiring a telecommunication system between the ends of the protected circuit.

Pulse code modulation (PCM)

Method of modulating a series of regularly recurrent pulses of the carrier signal according to the bit sequence of the modulating signal which is sampled and converted to a digital form.

Redundancy

The characteristic of a device, piece of equipment or a system by which it continues to perform all or some of its function following the failure of components or subassemblies.

Relatively selective protection system.
Non-unit protection system

Graded protection system. A protection system, the operation and selectivity of which are solely dependent on the measurement of electrical quantities at one end of the protected section, associated with time.

Reliability

The probability of not having an incorrect operation. (The probability of not having a failure to trip - or not having an unwanted operation) (compare with availability and dependability and security).

Remote back-up protection

A back-up protection equipment or system located in a substation remote from that substation in which the corresponding main protection is located.

Residual current/voltage protection system

A protection system operating for three times zero-sequence current ($3I_o$) and/or three times zero-sequence voltage ($3U_o$). US = $3V_o$

Security

The probability of not having an unwanted operation. (compare with reliability, dependability)

Segregated protection

Normally consists of one protection for each phase (compare with protection with mixing transformer. Non-segregated protection).

Selectivity

The ability of a protection system to detect a fault within a specified zone of a network and to trip the appropriate circuit-breakers to clear this fault with a minimum of disturbance to the rest of that network.

Series fault

A condition for which the impedance of each of the three phases are not equal. Usually caused by the interruption of one or two phases.

Shunt fault

A fault that is characterized by having a fault between one, two or more phases or between phase and earth.

Single (three) pole automatic reclosing

An automatic reclosing operation intended to reclose one (three) poles of a circuit breaker after a single (poly) phase power system fault.

Source impedance

The equivalent impedance of the network viewed from one point in the direction of the source of supply. The short circuit power at this point is inversely proportional to the source impedance.

Space signal

For a telecommunication system based on a two-condition modulation the space signal represents the condition in which the digit 0 is transmitted. In amplitude modulated systems this usually corresponds to the tone-off condition while in frequency shift keying modulation systems this usually corresponds to the high frequency condition.

Spontaneous fault

Hard ware fault. A failure of a protection system to function as required due for example to a defective sub- circuit, that may be identified by test procedures (compare with principle fault).

Static protection

An electrical protection in which the characteristic response is mainly developed by electronic, magnetic, optical or other components without mechanical motion.

Substation local back-up protection

A back-up protection equipment or system which is energized from instrument transformers located within the same substation as the corresponding main protection equipment.

Note: The substation local back-up is not energized from the same instrument transformer as the main protection system. (Compare with circuit local back-up protection)

Switched distance scheme

A distance protection in which measuring units are selected to measure more than one type of shunt fault. Phase selectors are used to select the appropriate measuring quantities for each type of fault. The same measuring units are used to provide all zones of protection.

Telecommunication system

A link between ends of a protected circuit permitting the exchange of information in the form of voice-frequency signal and/or teleprotection signals, composed of telecommunication equipment and the associated physical link.

Example: Power line carrier, microwave, pilot wire, optical fibre etc.

Teleprotection channel

a) The frequency band at disposal on the telecommunication system in order to permit the transmission of protection signals in both directions.

a) System composed, for testing purpose, by teleprotection equipment connected back-to-back without the associated telecommunication system.

Teleprotection equipment

Equipment designed to be used in conjunction with a protection system requiring a telecommunication system between the ends of the protected circuit, to transform the information given by the protection equipment into a form suitable for transmission.

Teleprotection system

System composed of the teleprotection equipment and its associated telecommunication system, in a protection system using telecommunication, between the ends of the protected circuit.

Tie line

A power transmission line which interconnects two or more power systems, for example power lines between countries.

Transfer impedance

The equivalent impedance between two points on a network representing all parallel paths between those two points.

Transmission time

The time elapsing in a teleprotection channel between the instant of variation of the input quantities under stated conditions at the transmitter equipment input occurs and the instant at which the corresponding variation of the output quantities occurs at the receiver equipment output excluding propagation time due to the telecommunication system.

Two circuit breakers system

A switchyard arranged with two circuit breakers per circuit.

Unbalanced power system

A power system is unbalanced when the three voltages/currents of the three phases do not have the same magnitude or when the angles between phases are not equal.

Underreaching

The condition of a distance protection system when the zone setting corresponds to an equivalent distance shorter than the length of the protected circuit.

Unselective tripping

The clearance of a fault from the network by the operation of more circuit breakers than are needed.
US = overtripping

Unwanted operation

Overfunction. The incorrect operation of a protection system either without any power system fault (non system fault) or for a system fault the protection system does not require to operate.

Zero sequence component

One of the sequence components which can exist in an unsymmetrical three phase system.
US = Zero phase sequence comp.

$$I_0 = \frac{1}{3} (I_{L1} + I_{L2} + I_{L3})$$

Zones of distance protection

Distance protection often have more than one impedance zone. These zones are commonly designated 1, 2, 3 etc with each succeeding zone set to operate at a higher impedance and with longer delay than the succeeding zone. These zone or a selection of them may be logically connected with singalling in varies mode. The signalling zone in a switched distance protection is called zone A in this report. A starting zone is also usually provided with the highest impedance setting and may have a tripping function with lag time.

4 POWER SYSTEMS

4.1 General

A power system can be sub-divided into generation, transmission and distribution.

Generation covers power stations and all aspects of electric power generation. Transmission deals with transmission of power over long distances at high voltages. Power stations and substations are connected to the transmission system. Distribution is normally effected at lower voltages and consumers are directly connected to this network.

4.2 Transmission

This report will deal with protection systems for transmission networks. Large transmission systems covering long distance are often formed at interconnecting smaller transmission networks by tie lines. The resultant network is often very meshed. This means that power stations and substations are connected to the network at different points and the direction of power flow in the interconnecting power lines may vary from time to time. Almost all developed transmission systems are of this type.

The voltages used for transmission differ from country to country and are normally in the 220 kV to 800 kV range. Lower voltages such as 130 kV are sometimes used. CIGRE SC34 and SC35 deal with protection and communication associated with transmission networks.

Transmission networks include power lines and busbars. Power transformers located at the busbars are used to transform power between networks operating at different voltage levels. Reactors and shunt capacitors may be connected to the network to provide voltage regulation. Series capacitors are sometimes connected in power lines in order to increase their power transfer capability.

The task of the protection system is to protect the network by isolating the faulty section and to prevent or limit damage to high voltage equipment in the case of power system faults.

4.3 Stability

Transmission networks may have stability problems. Normally networks are designed in such a way that one power line can be lost without any complete breakdown. If two lines have to be disconnected from the network at the same time during heavy load this can, in many situations, result in a comprehensive black out.

For this reason it is important for the protection system to trip selectively. This means that only the faulty part of the network must be disconnected and that the healthy part must be kept in operation. It is recognized that design-philosophy in transmission networks differs from country to country.

Nonselective tripping is not the only type of tripping occurrence which can cause a dangerous situation. A fault which is not cleared fast enough can create a power swing or an unstable situation in the network. Normally the greatest need for fast and selective fault clearance concerns faults close to centres of generation.

Planning engineers often ask for fast fault clearance for stability reasons. The alternative to fast clearance is often to build more power lines. This is generally more expensive than having a sophisticated protection system. Nowadays environmental restrictions often make it very difficult to build new lines.

4.4 Fault-Clearance-time

There has always been a demand for a fast acting protection system in a transmission network. However, at the same time the security of the protective system must be kept at a high level. Normally it is difficult to achieve fast protection and at the same time high security.

The fault-clearance time consists of two main components - the protection system operating time and the circuit breaker operating time -.

$$F = R + B \qquad (1)$$

F = Fault clearance time
R = Protection system operating time
B = Circuit breaker operating time

The protection system operating time can be subdivided into e.g. starting operating time, measuring operating time and operating time for tripping relays.

Also the circuit breaker operating time can be subdivided into mechanical operating time, de-ionising operating time and restriking operating time. A minimum oil breaker, for instance, has a very long restriking operating time.

The required fault-clearance time differs from network to network. With modern protection systems and modern circuit-breakers it is not difficult to achieve a fault-clearance time of 80-90 ms. Nowadays protection systems exist which can operate within 8-10 ms and circuit breakers which have an operating time of 30 ms which together give a fault-clearance time of 38-40 ms.

It is often a requirement from a stability point of view that the fault-clearance time shall almost be the same for faults at any position along a power line particularly if the line is short.

Teleprotection system must be used in order to achieve a fast clearance for all fault positions along the line. Normally the communication requires a time of 10-30 ms. If for example permissive underreach distance protection system is used, the clearance time for a fault in the remote end will be the sum of protection system operating time for a close up fault + teleprotection operating time + circuit breaker operating time. Formula (1) can thus be written. Compare with fig. 12:4.

$$F = P + T + B \qquad (2)$$

where T = Teleprotection system overall operating time
P = Protection equipment operating time
R = P+T = Protection system operating time

5 POWER SYSTEM FAULTS

5.1 General

Any unplanned change in the network is called a disturbance. It can be caused by a power system-fault, a non-system fault, or a network-fault.

A power system-fault is a fault in the network e.g. a three-phase short-circuit.

If a circuit breaker trips and there is no fault in the network the disturbance is caused by a non-system fault e.g. a fault in the protection system.

An overload, a power swing, an extreme voltage-drop, an extreme frequency-drop etc. in the network is called a network fault. (disturbance)

5.2 Causes of faults

Faults occur in all networks. It is impossible to design economically a network which will never have a fault. The main causes of faults differ from country to country. Faults can be caused by lightning, salt, pollution, sabotage and damage. The fault rate is normally higher on low voltage power lines than on high voltage power lines.

5.3 Types of power system faults

It is common to differentiate between shunt faults and series faults. Shunt faults are the most common. They are characterized by an flashover between phases or between phase and earth. Series faults are characterized by a different value of impedance in the three phases. A typical series fault is an involuntary interruption in one or two phases.

If two shunt faults occur on different points in the network the combined condition is called cross-country fault.

From table 5:1 one can see for one particular 400 kV network how system shunt faults are distributed by different fault-types. The table corresponds to a period of 32 years. Fig. 5:1 shows different kinds of power system faults.

Table 5:1. Distribution of shunt faults on fault types

Single phase	191	72 %
Two phases	59	22 %
Three phases	17	6 %

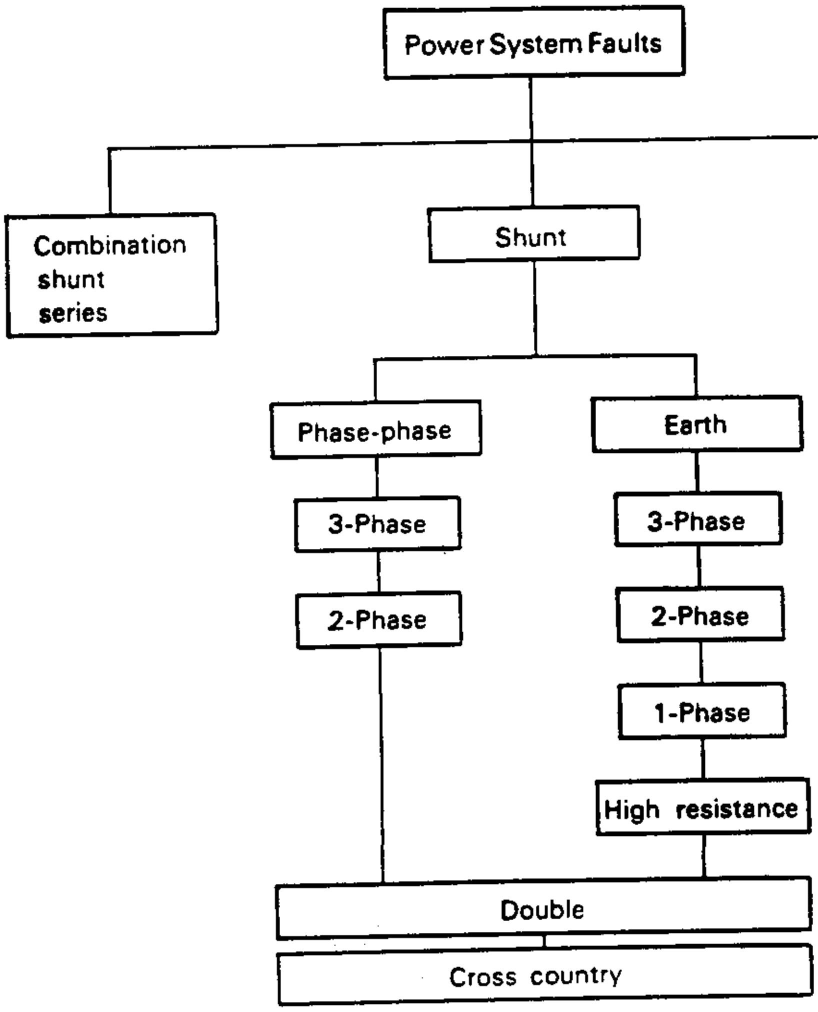


Fig 5:1 Different kinds of power system faults

5.4 Short circuit power

In a well developed power system the short circuit power (fault level) is normally very large. It is common to design high-voltage equipment for 35,000 MVA. This corresponds to 50,000 A per phase at 400 kV. In the case of single and three-phase faults particularly the thermal and dynamic stresses are severe. For this reason it is necessary to have a dependable and fast system for fault-clearing in order to minimize the damage.

In almost all transmission networks the neutral of each transformer is directly connected to earth. In the case of a fault between phase and earth there will be a single phase short circuit. The fault current will be of the same magnitude as a three-phase fault and sometimes greater.

All earth-faults will create unsymmetrical fault-currents. The sum of the phase-currents is no longer zero. The unsymmetrical situation will induce dangerous voltages in communication wires and in low voltage power lines. It also creates dangerous earth-potential because the fault current will flow in the earth. It is very important to have fast clearing times for such faults and in some countries even a very small earth fault current must be cleared. The small current occurs when there is a high resistance in the fault location or if there is a series fault.

5.5 Symmetrical components

All unsymmetrical three-phase systems can be divided into three symmetrical components. They are called

The positive sequence component
The negative sequence component
The zero sequence component

The three components are shown in fig 5:2. This fig is just an example of a short circuit current for a single phase fault. If there are other types of fault the situation will be different.

During normal operation the three-phase system is in general symmetrical and only the positive sequence component exists.

When a fault occurs the power system will be unsymmetrical except when the fault is a symmetrical three-phase fault.

The negative component causes stress and heating in the generators. Turbo machines are particularly sensitive to this component.

The zero sequence component causes induction in communication lines and gives a rise in earth potential mentioned earlier.

From the protection point of view it is interesting to know that these two components are almost zero during normal operation while they have a value when there is an unsymmetrical fault. For that reason a protection system based on negative or zero sequence components can be set very sensitive.

Overcurrent and distance protection systems are fed with phase quantities L1 L2 L3 (R S T) and the setting of these relays must be checked against load current and load impedance respectively so that no unwanted operation will occur during heavy load.

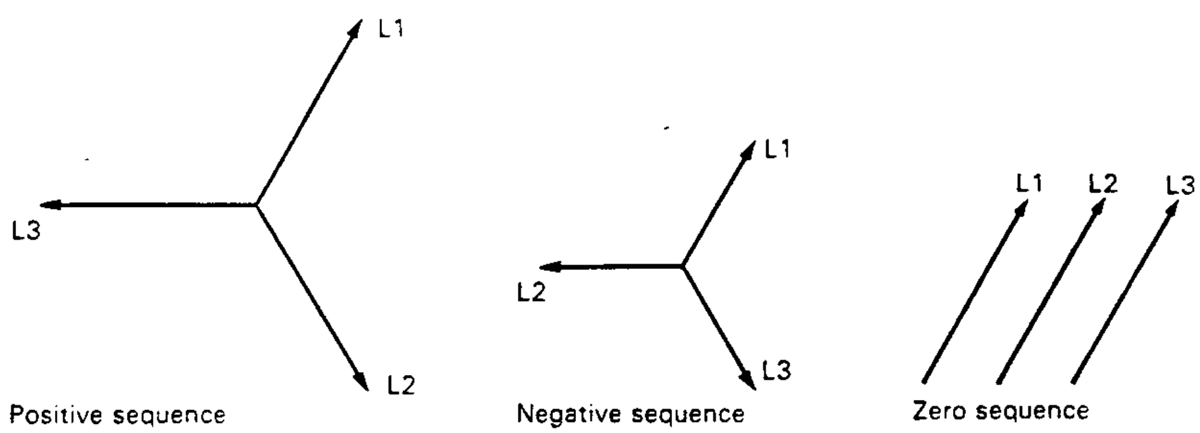


Fig 5.2 The three sequence component.

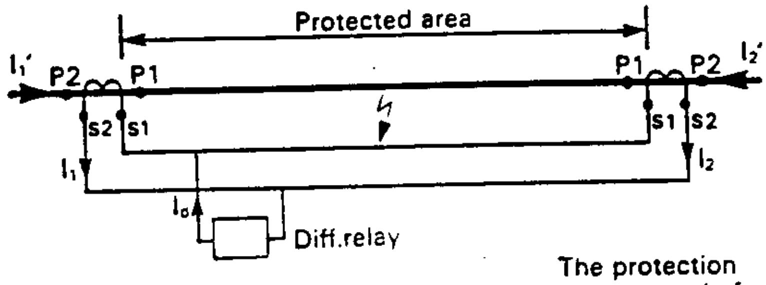
6 PROTECTION SYSTEMS

6.1 General

The protection system for a whole network is structured into power-line-protection systems, busbar-protection systems, transformer-protection systems and generator-protection systems. When reactors and capacitors are connected to the network they usually have their own protection systems. This structure seems to be the same all over the world and it seems to be the same even if there are electromechanical or electric digital components.

Protection-systems are commonly divided into two groups with reference to their principal main function. One is called absolutely selective (unit) protection and the other is called relatively selective protection (non-unit, graded) protection. The difference between these two principles is shown in fig. 6:1 and will be further elucidated in due course.

Absolutely selective protection
Unit protection

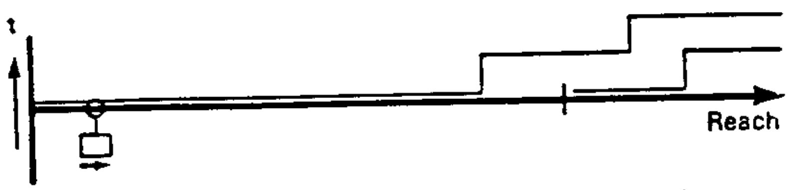


I_d = Differential current

$I_d = I_1 + I_2$

The protection operates only for faults inside the protected area
This protection has no back-up features

Relatively selective protection
Graded protection, non-unit protection



Graded protection can be set:
- Current-graded
- Impedance-graded
- Time-graded

This protection has back-up features

Fig 6.1 Absolutely selective and relatively selective protection systems

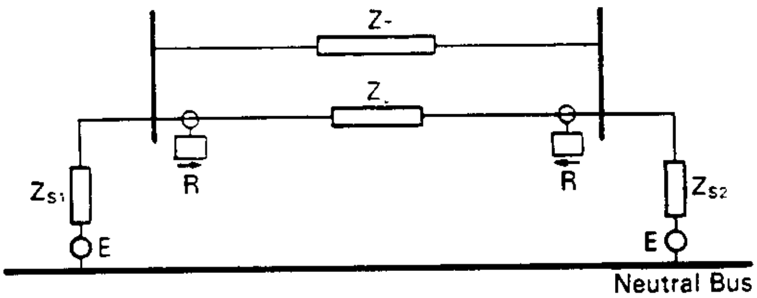
6.2 Power line protection systems

Power line protection systems can be of different kinds. The most common are distance protection, carrier-phase-comparison, longitudal-differential protection and direction comparison protection.

The distance protection is a relatively selective protection and the other three are absolutely selective protections. The last three require, for their main function, telecommunication between each end of the power line. They are described in chapter 10.

6.2.1 Distance protection systems

The very first protection system used on transmission networks was worked on the overcurrent principle. When networks were extended and became more meshed this kind of protection was unsatisfactory. It was almost impossible to get a selective setting. This protection needs a great deal of knowledge about the magnitude of the short-circuit current and this current is dependent upon the magnitude of the source impedances. The source impedances for their part differ from time to time. In order to get selectivity one had to delay the protection or change the setting from time to time. This was very inconvenient and delaying of protection on the transmission network was not acceptable in the long run. Sometimes also the fault current was less than the highest load current which made it difficult to use over current protection system. The equivalent circuit of the network around a power line is shown in figure 6:2.



Z_T = Transfer Impedance
Z_S = Source Impedance
Z_L = Impedance of the protected line
E = Equivalent EMK
R = Protection system

Fig 6:2 The equivalents of the network

It was necessary to find a protection principle which was independent of the variation of source impedances. Very soon it became evident that the impedance of a line was constant and independent of the source impedances. So the new protection was based on power line impedance measuring and was an underimpedance scheme. Under normal conditions the protection measures the load impedance which can be written $U_L/I_L = Z_L$. If there is a fault on the line the impedance in the loop protection-fault-protection will be less than the load impedance and the protection will operate. The underimpedance on a protection principle has been developed very much over the years and nowadays it is called distance protection. It is very common to study the reach of distance protections in the R-X plane. In this diagram the power line, the operating curve and load-impedance can be shown. A typical R-X diagram for distance protection is shown in fig. 6:3.

A distance protection system uses phase-quantities for its measurement. If accurate settings are required the load quantities must be superimposed on the fault-quantities and the calculations can be complicated.

Distance protection is a relatively selective protection. This means that selectivity is achieved without any comparison from the remote end and, thus, it does not need any telecommunication systems for its basic function. The settings of impedance and time are for that reason very important. A distance protection has many zones. The first zone is instantaneous and the second and third zones are delayed. It is important that the first zone will not overreach so it is set to 80-90 % of the line length. The safety margin is thus 10-20 %. Sometimes it is necessary to have higher margin due to the mutual impedance of parallel power lines.

This margin is needed for tolerances of line impedances, tolerances of periphery equipment such as CT and VT, tolerances of protection systems.

The main task for the second zone will be to cover this safety margin of the first zone and normally the second zone is set not less than 120 % of the line. It is delayed 0.3-0.5 s. The reach of a distance protection is shown in Fig 6:3.

There are many different kinds of distance protection. It is common to distinguish between full schemes and switched schemes. A full scheme has usually one measuring unit for each phase and each zone while a switched scheme has <u>one</u> common measuring unit for all phases and all zones. It means that the switched scheme must have starting elements which will give information to the measuring unit as to which phase or phases and zones are involved to be measured. Fig 6:4 shows the main differences between full schemes and switched schemes.

Nowadays there are many distance protection systems which can be said to be a mixture between a full scheme and a switched scheme.

When measuring phase-to-phase faults only the positive and negative sequence impedances of the line are taken into consideration. When an earth fault is measured, the zero-sequence impedance in the line must be considered. In a switched scheme this is normally organized in the same logic as switching between phases and zones. In a full scheme covering faults between phases and between phase and earth, separate measuring elements are used for earth faults.

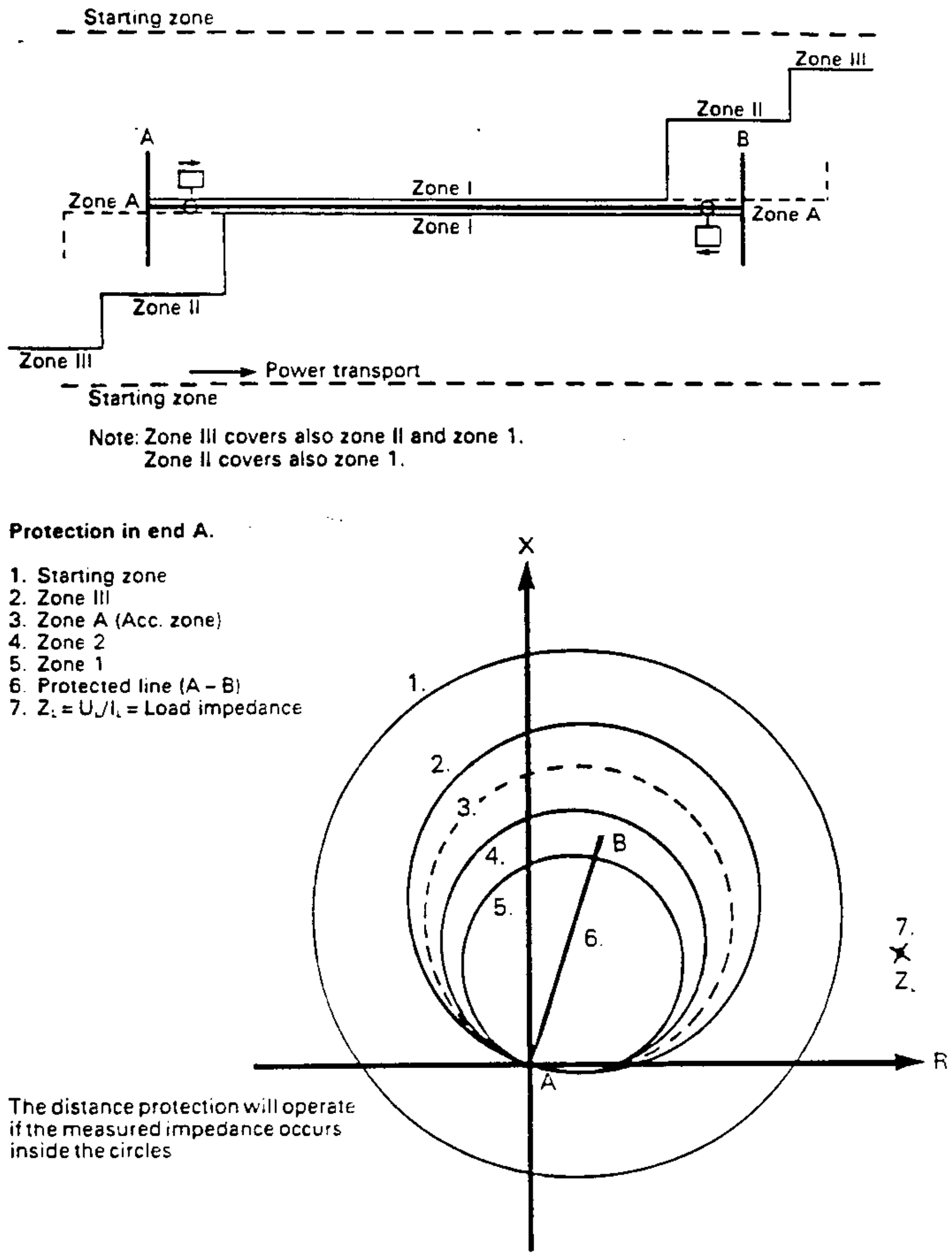


Fig 6:3   The reach of a distance protection

As said before the instantaneous zone of the distance protection covers only 80-90 % of the line. In many applications on transmission networks it is not satisfactory for a fault at the far end of the line cleared in the second zone (0.4 s).

There are many methods of speeding up the fault-clearance time for a fault at the far end. Common to all methods is the need for that a telecommunication system between the ends of the power line. Almost all these methods are described in chapter 11.

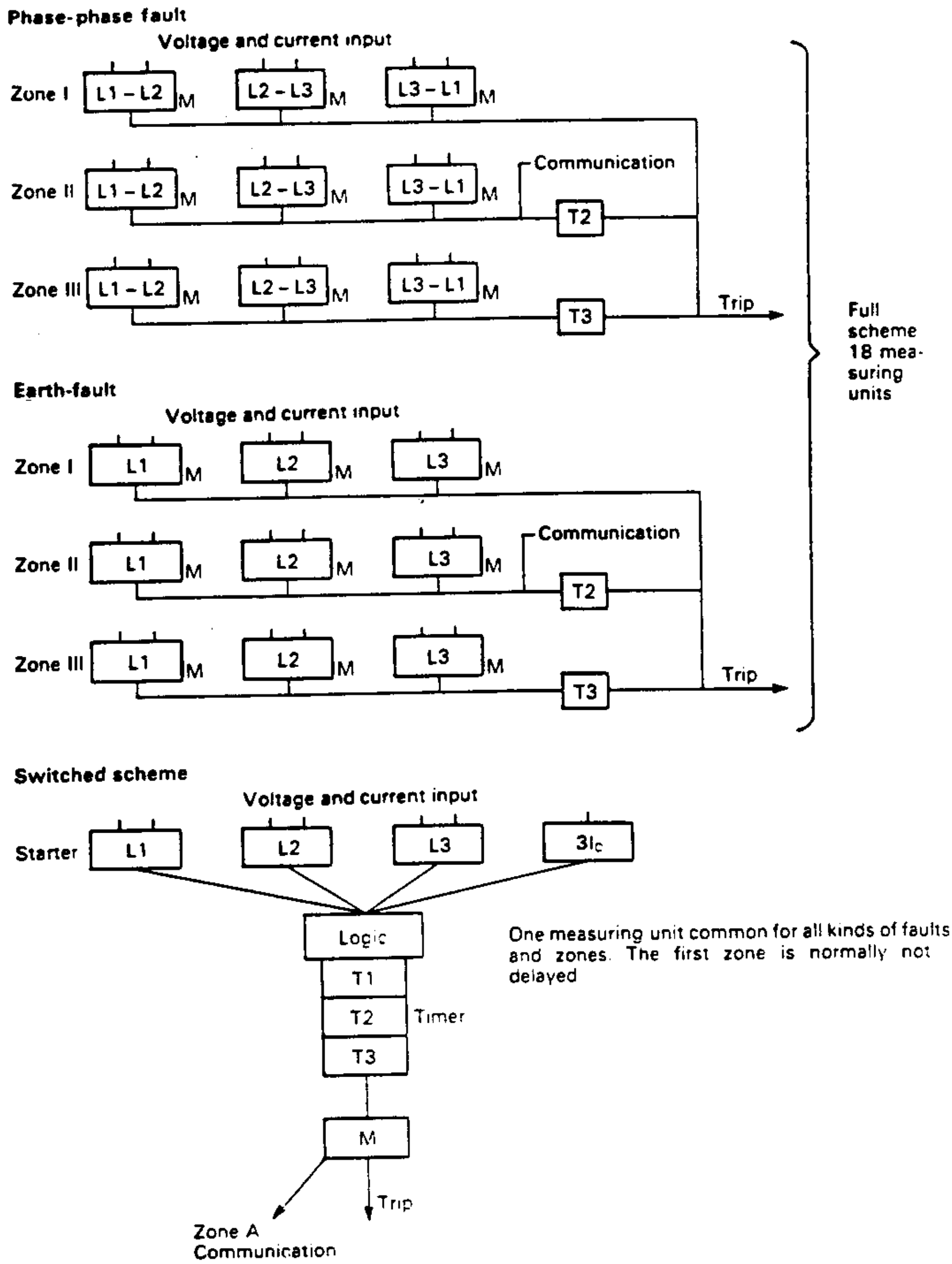


Fig 6:4 Example of a full scheme and a switched scheme of distance protection

When a teleprotection system is connected to a distance protection of full scheme, zone 2-measuring units(M) are normally used as criteria for received signal. If instead a switched scheme is used the received signal will switch zone 1 from underreaching to overreaching. The overreaching zone is called zone A in this report. See fig 6:4. These zones can also be used for sending. This is described more in detail in chapter 4.

When a line is energized the instantaneous zone normally covers more than 100 % of the line. Shortly after the breaker has been closed the reach will be switched to the normal reach of 80-90 %. This function is called the check-line function.

6.2.2 Phase comparison protection systems.

The phase comparison protection system is an absolutely selective (unit) protection system. The principle is based on the measurement of the phase angle difference between the currents at the ends of a protected power line. If the angle is small there is an external fault and if the angle is great there is an internal fault.

To be able to make this comparison it is necessary to have a telecommunication system between the power line terminals. Therefore, the basic principle relies on telecommunication. No protection exists if the communication fails. For that reason a relative selectively protection is normally added to the protection system. The protection system is described in chapter 10.

6.2.3 Longitudinal differential protection systems

Differential protections are all absolutely selective (unit) protections. The basic principle is to measure the magnitude and angle of the currents coming into the protected area. During normal operation the sum is zero.

A power line protection system requires telecommunications between the power line terminals.

The most common media for this protection are pilot wires which means that this protection is mostly used for short lines.

Nowadays longitudinal differential protections have also been installed for long lines. The telecommunication system is usually power line carrier or microwave.

Longitudial differential protection also requires a telecommunication system for its basic principle. Without any communication there is no protection. For that reason normally a relative selective protection is added to the protection system.

6.2.4 Direction comparison protection systems

This protection is also an absolutely selective protection and requires for its basic function a telecommunication system between the ends of the power line.

This protection compares the direction of the fault current in both ends of the power line. If the direction measurements indicate that all the currents are flowing into the protected area this signifies an internal fault. If one of the measurements indicates current flowing out of the protected area this signifies an external fault.

This principle is very similar to the permissive overreach distance protection system and the residual current comparison protection system. They are described in section 11.

6.3 Busbar protection systems

Busbar faults are usually caused by flash over in the high voltage equipment. Sometimes faults are caused when earthing equipment is applied to the busbar before the busbar is disconnected from the network (human error).

If there is no busbar protection a busbar fault will be cleared by the power line protection in the neighbouring stations by the second zone (0.5 s) and the transformer back-up protection systems in the faulty station needs at least the same time for clearing the fault current coming from the transformer.

On a transmission network this long fault clearance time is unsatisfactory. From the operating point of view it is confusing when a power line protection system trips in a healthy station because of a busbar fault in a neighbouring station. If busbar protection is used, then not only with the fault clearance time be reduced but one's understanding of what has happened in the network will also improve. When a busbar fault occurs a lot of circuit breakers have to trip in order to isolate the faulty busbar from the network. This is a very dangerous situation for the network. For that reason it is important to have a layout of the station so that only a part of the whole station will be lost in case of a busbar fault. To be able to discriminate between the healthy and faulty part of the station busbar protection must be used. Fig. 6:5-6:8 show the most common layouts of stations and how busbar protection is arranged.

Nowadays almost all busbar protection systems are based on the principle of differential quantities. During normal operation the sum of all currents into the busbar is zero while during a fault on the busbar there is a differential current. The differential protection scheme can be of two kinds, high impedance or low impedance scheme. In high impedance schemes the differential relay is a voltage relay while in low impedance schemes it is a current relay. Busbar protection schemes using other principles are also available.

Precautions against unwanted tripping are very important for a busbar protection system. The protection must be stable for a fault outside the protected area. Current transformers performance is a very important factor.

If the switch-yard has the possibility of switching one circuit from one busbar to another there will be a need for switching in the current circuits of the busbar protection. This switching is usually made automatically and it must be designed very carefully, without any interruption in the circuit. To avoid an unwanted operation there is an extra busbar protection system which covers the whole station and, consequently, there is no switching in this current circuit. For tripping it is required that both busbar protection systems must operate. There will be two contacts in series in the tripping circuit, resulting in extra security of the busbar protection. The principle is shown in fig 6:8.

There are some fault locations, normally between circuit breakers and current transformers, on a busbar for which the whole fault current cannot be cleared by the busbar protection. The circuit is still feeding the fault after busbar protection operation. For these fault locations intertripping by telecommunication system is often used, see figs 6:6, 6:7, 6:8, 7:6.

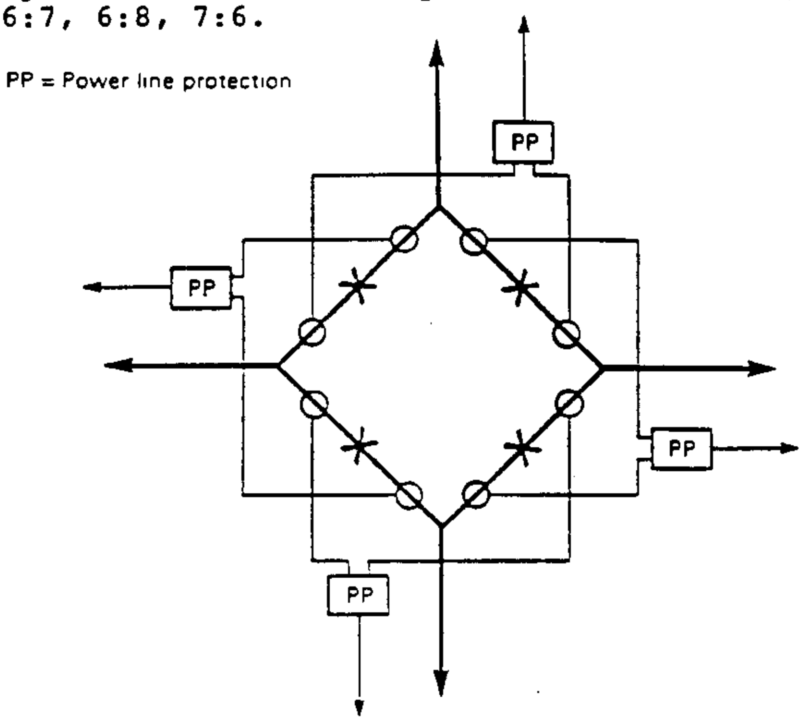
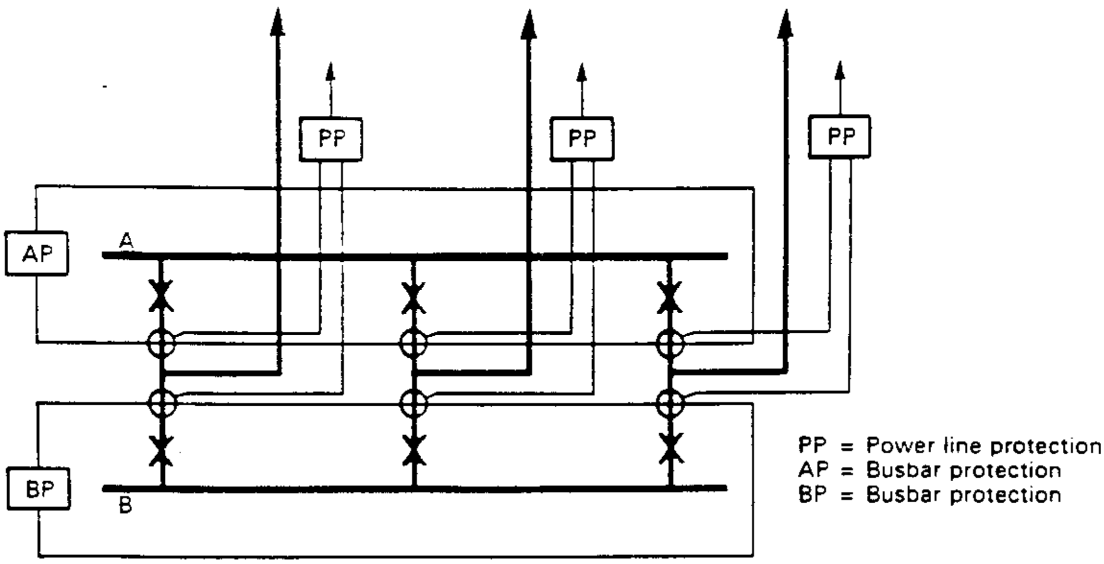


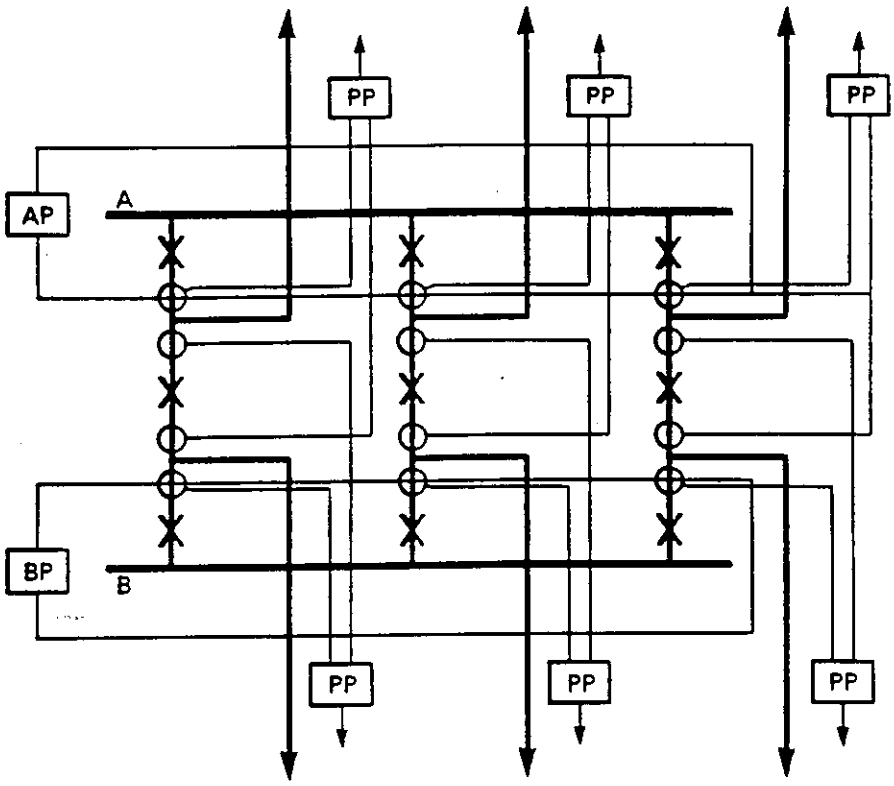
Fig. 6:5 Ring busbar system (four corner system)



In the event of a fault on busbar A the network will, after busbar protection-operation, still be intact via busbar B.

In the event of a fault between the current transformer and the circuit breaker the fault will still be fed from the adjacent station after the busbar protection has tripped. This fault can be cleared from the adjacent station by the second zone of the power line protection or by letting the busbar protection intertrip by means of telecommunication. Compare fig. 7:6.

Fig 6:6 2-circuit breaker system

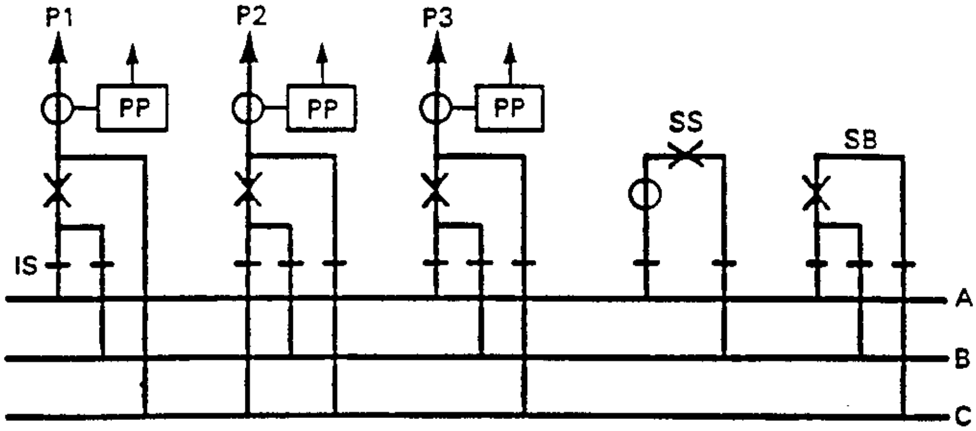


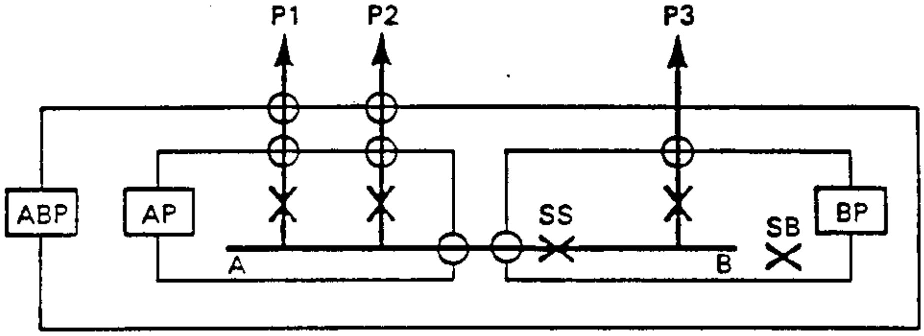
PP = Power line protection
AP = Busbar protection
BP = Busbar protection

In the case of a fault on busbar A the network will, after busbar protection-operation, still be intact via busbar B.

A large part of the switchyard will be protected by power line protection. A fault between a current transformer and a circuit breaker will still be fed from the adjacent station after the busbar protection has tripped. This fault can be cleared from the adjacent station by the second zone of the power line protection or by letting the busbar protection intertrip by means of telecommunication. Compare Fig. 7:6.

Fig 6:7 1½ circuit breaker system





A simplified diagram of the figure above (P1 and P2 connected to A and P3 to B)

Switching in the CT-circuits for protection AP and BP.
No switching in the check zone ABP.

SS = Sectionalizing circuit breaker
SB = Stand-by circuit breaker
PP = Power line protection
AP = Busbar protection
BP = Busbar protection
ABP = Check circuit zone
IS = Isolator

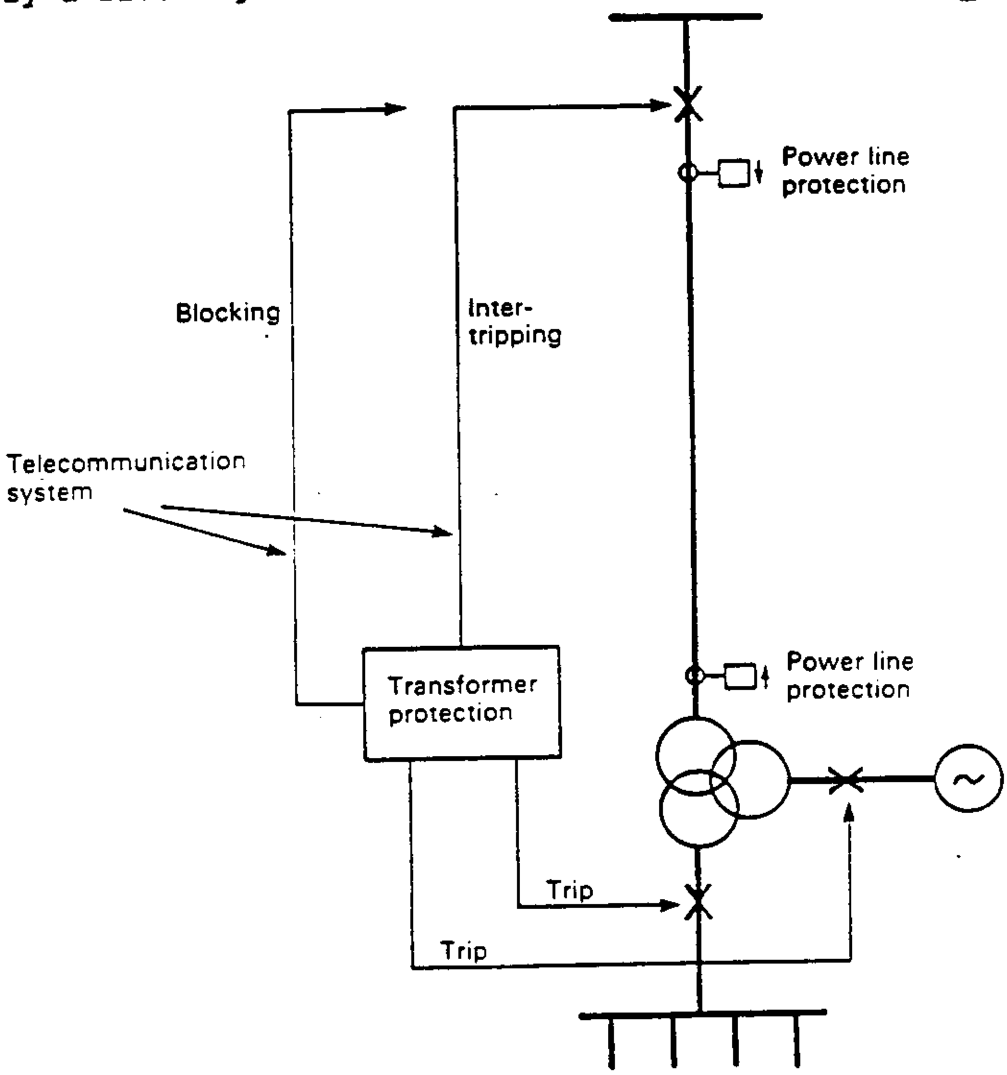
Fig. 6:8 Double main busbar with transfer bus, ABC-system

6.4 Transformer protection systems

There are many different kinds of power transformers. They can be divided into generator-transformers and system-transformers. The latter normally transform between networks. They could be auto-transformers and/or fullwinding transformers. Two, three or more windings can be placed on the same core.

It is quite common to protect a transformer with differential protection (absolutely selective protection). When transformers are energized it is common to receive an inrush current. This current will appear as differential current and the differential protection will trip. Inrush current consists of many harmonics and the second harmonic is significant for the inrush. Thus the differential protection of the transformers is restrained, usually to the second harmonic, in order to make it possible to energize the transformers without any immediate tripping. Buchholz relay and residual current protection are also considered as internal fault protection. They are more or less redundant to each other. Overcurrent-, underimpedance-and earthfault protection systems are often used as back-up protection for external faults.

Sometimes the circuit breaker on the high voltage side is placed in the adjacent station in order to economize on circuit breakers. In this case the transformer protection must send an intertripping signal to the circuit breaker by a telecommunication system. In the case of an internal fault the closing function of the circuit breaker will be blocked by a blocksignal. It is shown in figure 6:9.



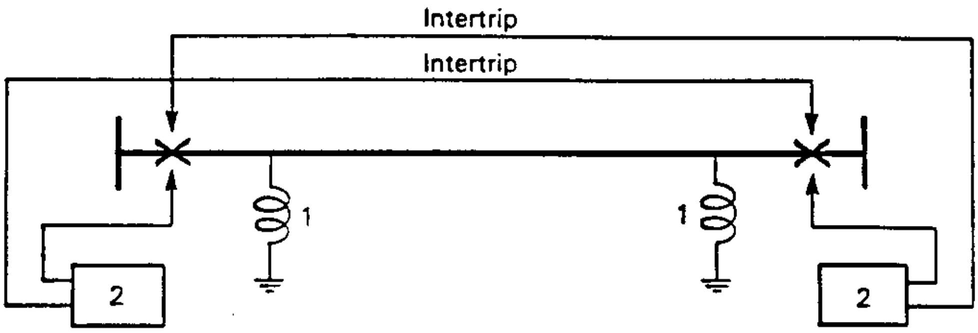
The transformer protection normally consists of differential protection, buchholz protection, overcurrent protection, underimpedance protection, residual current protection. The absence of circuit breaker on the high voltage side requires intertripping system. In the event of an internal fault all the closing functions of the circuit breaker will be blocked.

Fig 6:9 Transformer protection system; economizing of circuit breakers on the high voltage side

6.5 Reactor protection systems

Reactors are used to make it possible to regulate the voltage on the network. It is common to place reactors on the high voltage line in order to compensate for the capacitive generation.

Normally these reactors have no circuit breakers. Therefore the reactor protection must, in the case of reactor-fault, send an intertripping signal to the ends on the power line. This is illustrated in figure 6:10. The reactor protection system usually consists of an overcurrent protection and a differential earth-fault protection.



1. Reactor for compensation of the capacitive generation
2. Reactor protection

There are no circuit breakers for the reactors. The reactor protection must intertrip at both ends of the power line and the automatic reclosing will be blocked.

Fig 6:10 Reactor protection systems

7 FAULT CLEARANCE PHILOSOPHY

7.1 General

The kind of philosophy used in fault clearance differs from country to country. For instance an unwanted tripping can be preferred to a failure to trip etc and this is often referred to the way in which the power system is planned and designed. In the following the basic words used in this field are described and different philosophies are mentioned.

7.2 Unwanted tripping

Unwanted tripping can occur spontaneously, for instance, a component in the protection system breaks down. Normally a good transmission network should be able to withstand such an unwanted tripping. It is much more dangerous for an unwanted tripping to occur on an adjacent line to a faulty line. This is also called nonselective tripping. Many networks are not designed to lose more than one line at the same time without losing their stability, in particular during heavy load conditions.

7.3 Failure to trip

The worst incorrect operation is normally failure to trip. This can be due to either the protection system or the circuit breaker failing. Often it leads to a stability disturbance and breakdown of the network. The damage to equipment will probably be comprehensive because of the high fault level and the long clearance time.

7.4 Reliability, dependability, security

The reliability of protection systems is very important on transmission systems. An incorrect operation can cause a severe disturbance. Normally protection systems are more sophisticated in transmission power systems than in distribution systems. The costs of protection systems compared with total costs of a station are less for transmission power systems due to the very high costs of extra high voltage equipment.

Incorrect operation commonly divided into spontaneous (hard ware fault) and principal (software fault) incorrect operation. A spontaneous fault is normally caused by a broken component etc. A principal fault can usually be referred to a planning or design defect. Principal faults cannot normally be discovered by maintenance tests. See fig 7:1.

It is also common to divide incorrect operations into unwanted tripping and failure to trip. Sometimes an unwanted tripping can be preferred to failure to trip and sometimes the contrary. Normally power line protection systems are designed as the first mentioned and busbar protection is designed as the second mentioned. The saying goes that power line protection is designed with high dependability and busbar protection with high security. High dependability and security give high reliability. An unwanted tripping or a failure to trip can be caused by a spontaneous fault or a principal fault in the protection system. Normally the number of unwanted trippings increase with dependability and failure to trip increases with security increases. Fig 7:1 and 7:2 summarize what has been said in this section. More details concerning this aspects okn teleprotection systems will be given in chapter 12.

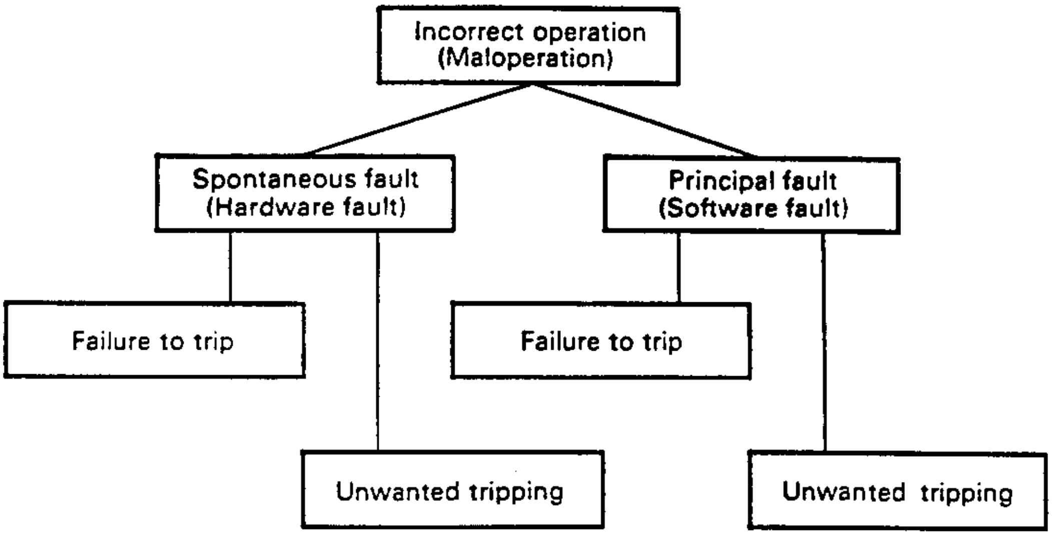
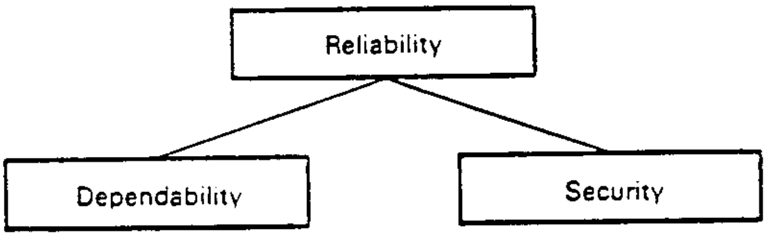


Fig 7:1 Incorrect operation of a protection system can be caused either of a spontaneous fault or a principal fault. Both can lead to either a failure to trip operation or an unwanted tripping



High dependability and high security means high reliability

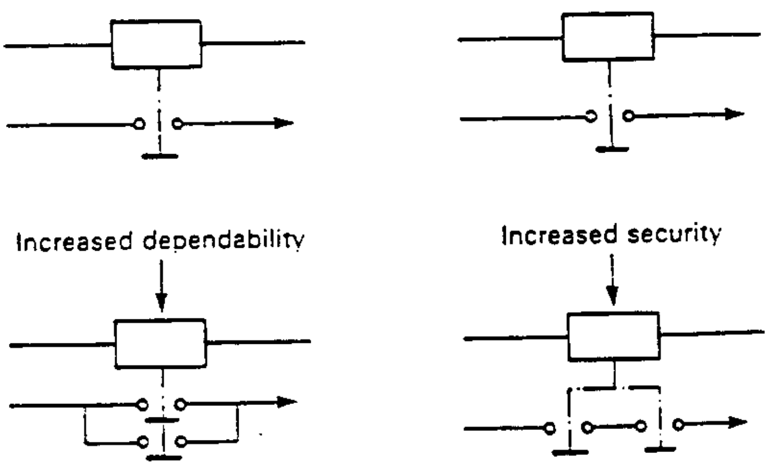


Fig 7:2 Relationship between incorrect operation and reliability

7.5 Remote back-up protection systems

Almost all power companies have the following philosophy particularly if the power systems are very well developed.

If a protection system or a circuit breaker fails to trip in the event of a fault on the network there must be other protection systems or/and circuit breakers to take over the task of clearing the fault from the network.

Consequently, there must be back-up protection and back-up circuit breakers. The next step is to define how sophisticated the back-up protection shall be and this differ from country to country. It depends upon the requirement of fault-clearance-time and selectivity, probability of fault, personnel security etc.

The very first type of back-up protection was called remote back-up. In this scheme the second or the third zone of a protection system had to be able to clear faults on the next line section. The fault-clearance-time was long and the selectivity unsatisfactory and sometimes this kind of back-up was not able to clear all kind of faults.

However, remote back-up is still used on simple network configurations. A typical remote back-up function which is very often used, is the back-up for busbar protection. The second zone of the power line protection in neighbouring stations will give the back-up function for the busbar protection in the faulty station.

7.6 Local back-up protection systems

When a network is extended, it is often found that remote back-up is unsatisfactory due to the resulting long clearance time, nonselectivity in tripping and difficulties in obtaining a sensitive enough setting to cover distant faults on the adjacent line.

The local back-up system was then introduced. This scheme is characterized by using a protection system in parallel with the main protection system. It is also called a redundant system. The degree of redundancy differs of course from network to network depending upon the philosophy of fault clearance. High voltage equipment such as circuit breakers and instrument transformers is not normally duplicated because of the high cost. The DC-supply is separated for the two protection systems. Different batteries are normally used.

The local back-up was a very simple protection system. It was very often an overcurrent protection and residual current protection with long operating time.

Nowadays local back-up has been developed so as to have almost the same features as the main protection. Sometimes the two protection systems are called MAIN1 and MAIN2. In order to minimize the number of principle-fail-to-trips (increasing the dependability) it is sometimes recommended that MAIN1 be of a different principle to MAIN2. Fig 7:3.

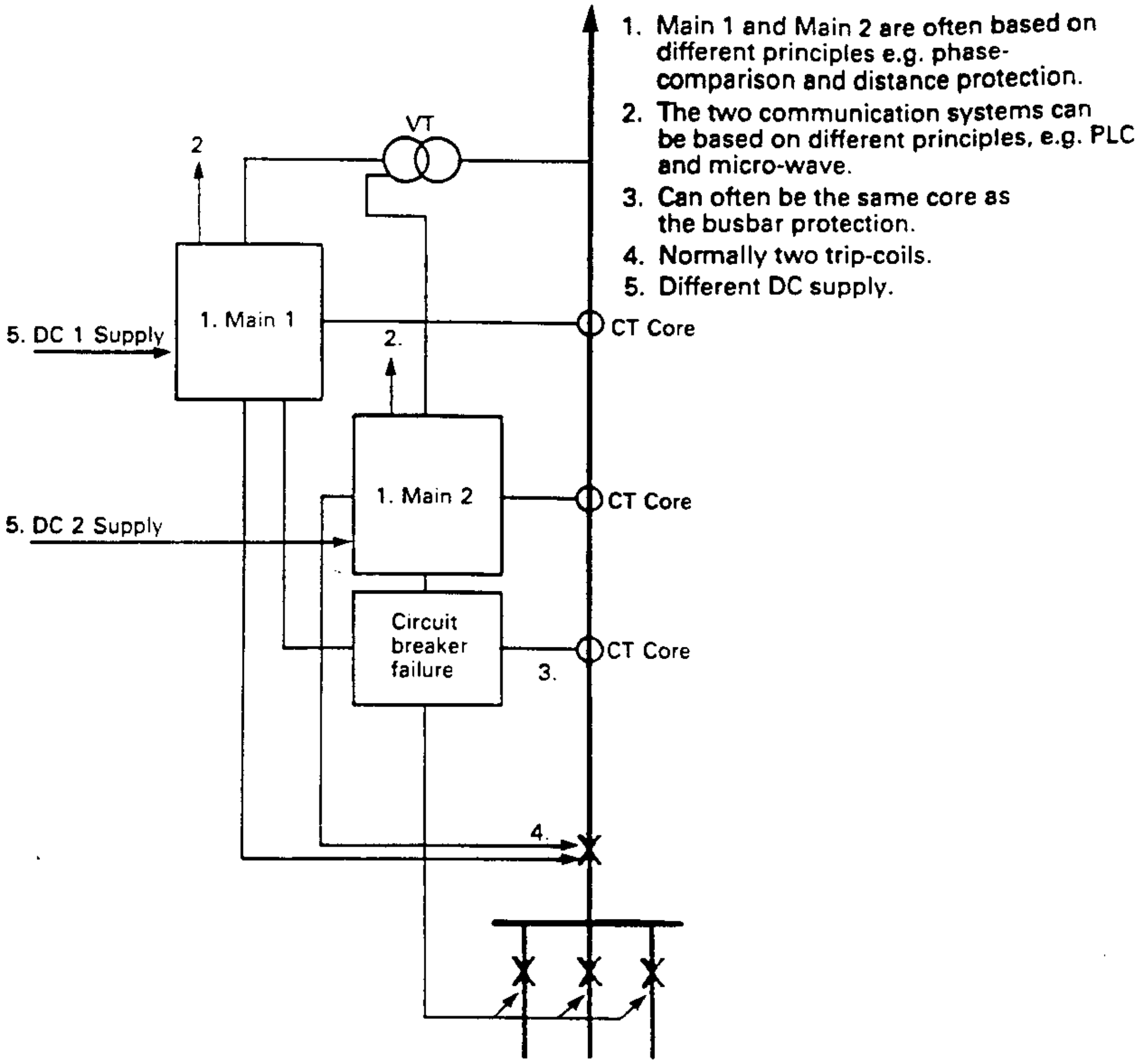
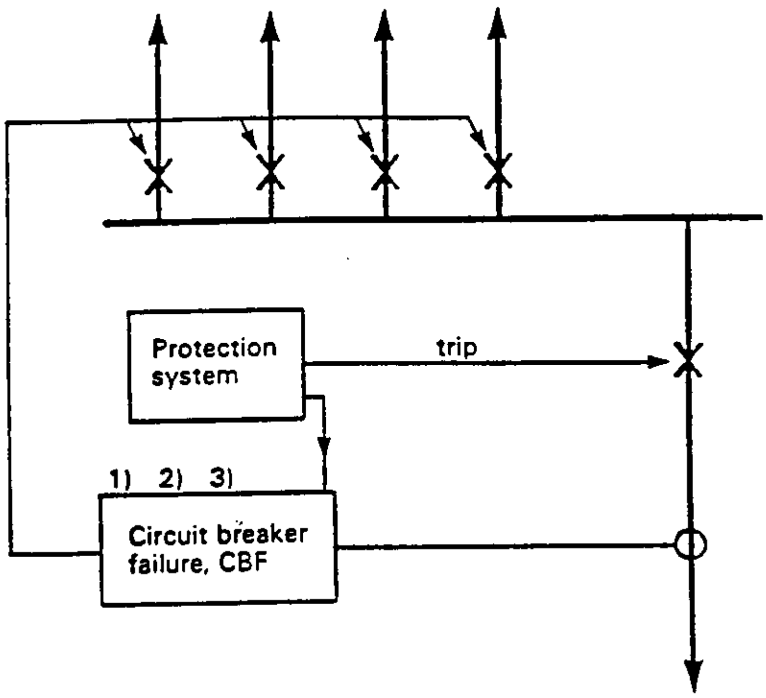


Fig 7:3 Circuit local back-up protection system

7.7 Circuit-breaker failure protection systems

In order to get a complete back-up protection system it is also necessary to take the circuit breakers into consideration. Two protection systems are of no help if the circuit breakers fail to trip. Nowadays the redundant system also contains circuit-breaker-failure protection. This protection will, in the event of a circuit breaker failure, ensure that the adjacent circuit breakers take over the circuit breaking operation. Sometimes it is necessary to let the circuit breaker failure trip circuit breakers in adjacent stations by means of an intertripping signal. See fig 7:5. The circuit breaker failure protection often has an overcurrent check and the fault clearance time will usually not be less than 0.25 s from fault occurence. Fig. 7:4 shows the principle of a circuit-breaker-failure protection with overcurrent check. The overcurrent relays are usually closed during normal operation and must be reset quickly when the current disappears.

It is to be noted that a remote back-up system is satisfactory, there is no need for a circuit breaker failure protection because both the protection and the circuit breaker are covered by this back-up system.



1. CBF is initiated from the protection system and CBF will be disconnected a short time after the trip-signal has disappeared.
2. CBF has an overcurrent check. The current relays will reset quickly when the current in the power line has disappeared and the CBF will be disconnected.
3. CBF has a time-lag relay which is set with such a margin that the main circuit breaker can carry out its function before any tripping from the CBF.
4. Protection operating time; 5) Circuit breaker operating time; 6) Resetting time; 7) Margin; 8) Setting of the time-lag relay; 9) Fault-clearance-time

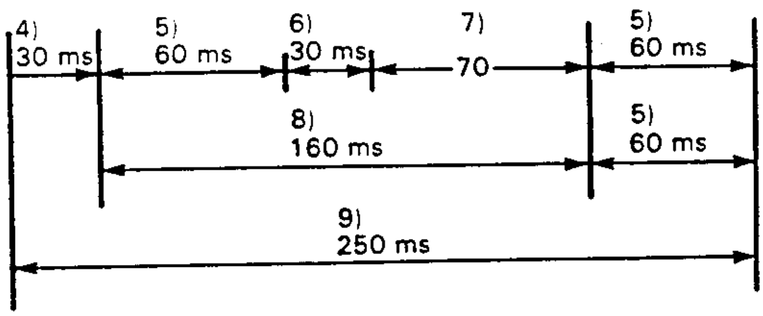
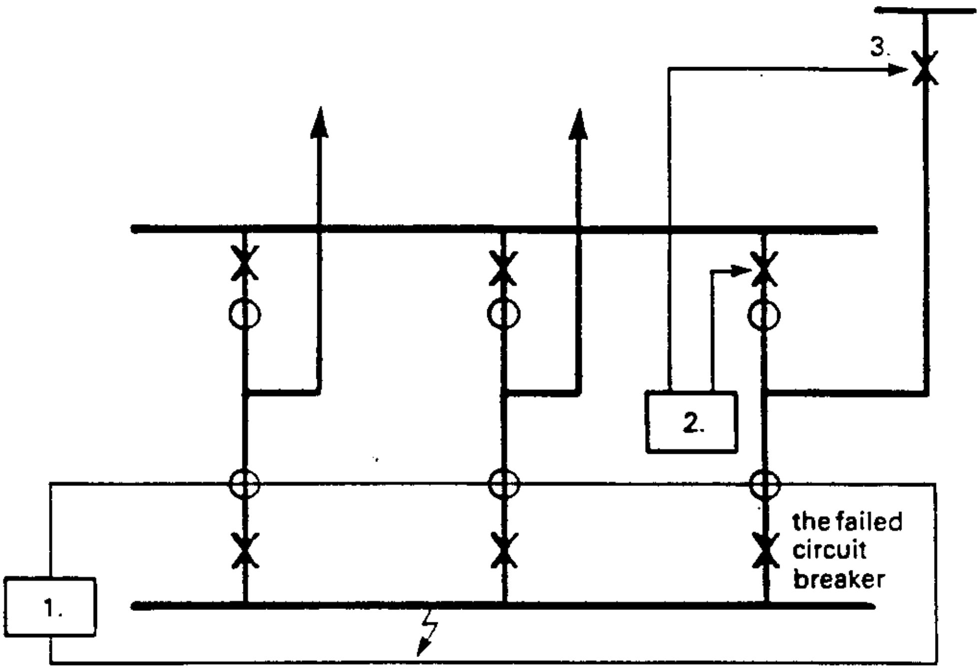


Fig 7:4 Circuit breaker failure protection systems



1. Busbar protection
2. Circuit breaker failure protection, CBF
3. CBF trips by means of intertripping system

Fig 7:5 Intertripping from the circuit breaker failure protection system

8 AUTOMATIC RECLOSING

8.1 General

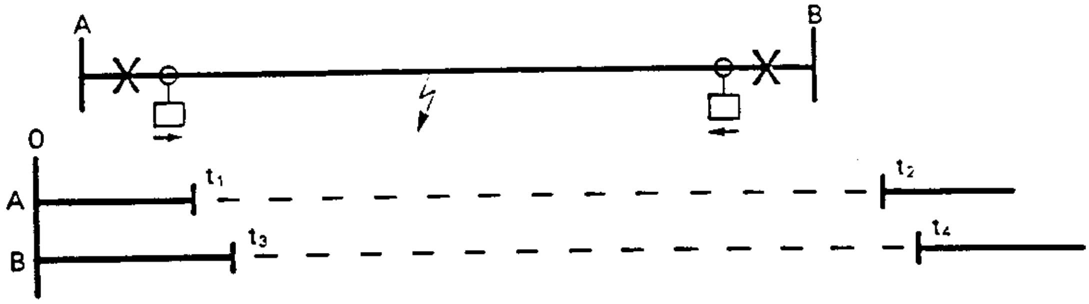
Faults on overhead power lines are often caused by transient overvoltages originating from lightning strikes. Normally the insulation will be broken through a flashover on the insulators on the towers.

If the current at the fault location is interrupted for a short time the fault location will be deionized and the power line will have full insulation when the line is reenergized.

This kind of fault is considered to be transient. A sustained fault will occur when the insulators are damaged and the conductors are perhaps broken and make contact with the gro und.

The number of transient faults compared with sustained faults differs from country to country. It is not unusual for 80 % of all faults to be transient.

These facts have encouraged engineers to develop automatic controls which will close the circuit breaker a short period after the protection system has tripped. The time needed for successfull reclosing depends upon the voltage level. Normally the dead time on overhead lines must not be shorter than 0.3 s. Fig. 8:1 shows the definitons of words used in the automatic reclosing field.



0-t_1 = Fault clearance time at the end A

0-t_3 = Fault clearance time at end B

t_1-t_2 = Auto reclose open time of the circuit breaker in A

t_3-t_4 = Auto reclose open time of the circuit breaker in B

t_3-t_2 = Dead interval (the effective dead time)

t_1-t_4 = Interruption time of the power transport (three phase faults)

Note: Normally no transport of power can occur when the line is faulty. Therefore the interruption time sometimes is said to be $0 - t_4$.

Fig 8:1 Definitions in the automatic reclosing field.

On high voltage networks automatic reclosing is usually used only when the protection system has tripped in the first zone. If the tripping signal comes later than 0.2 s-0.3 s from the fault occurrence the reclosing function is automatically blocked. In order to get automatic reclosing for all fault locations on the power line it is necessary to have almost instantaneous tripping. For that reason a telecommunication system must be used.

There are many different schemes for automatic reclosing. The commonese are single pole reclosing, three pole reclosing, delayed reclosing and automatic restoration.

8.2 Single pole reclosing

From Table 5:1 one can see that single pole faults are in the majority, particularly on high voltage systems. For that reason it is natural to open only the faulty phase when a single fault occurs. In the case of a multiphase fault there will be no automatic reclosing from this equipment. Instead the circuit breaker will trip in all three poles.

Single pole reclosing has the advantage, compared with three pole reclosing, that in case of a weak parallel network the healthy phases on the faulty line will provide important support to maintain the synchronism during the dead interval. See fig 8:2.

Recently it has become known from accidents and from calculations that faults near large generators will result in heavy stress on the shaft of the turbo generators. This stress will be worse if there is a sustained fault and the generator is reconnected to the fault by automatic reclosing. If the fault is a three-phasefault and three pole reclosing is used the generator can be damaged. The whole amount of fatigue for generator-shaft can be utilized in this case. For that reason many users prefer single phase reclosing instead of three phase reclosing near large thermal generating stations.

The disadvantage is of course the complication of relay protection, trip-circuit and circuit breakers etc. The protection system must be able to select the faulty phase from the healthy. - The protection must have a good phase selector -. Sometimes this can be difficult depending upon the network configuration. During the dead interval the network is in an unbalanced situation. There is, in fact, a series fault creating zero-sequence and negative-sequence currents which can cause maloperation from sensitive residual protection systems and negative sequence current protection systems.

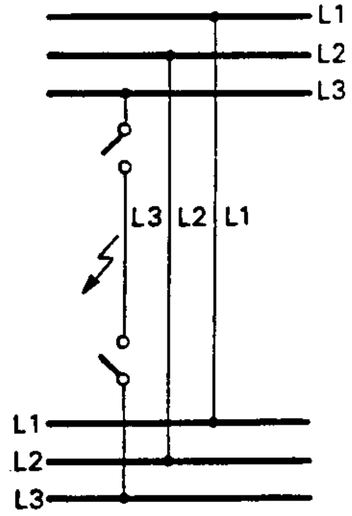
Normally the dead interval must be longer for single pole reclosing than for three pole reclosing because of the capacitive connection to the healthy phases.

8.3 Three pole reclosing

For high speed three pole reclosing all three poles of the breaker are open for all kinds of shunt faults. After the dead interval all poles are closed again at the same time without any check of voltage or synchronism. It is assumed that the parallel network is strong enough to keep the synchronism during the dead interval. See fig. 8:3.

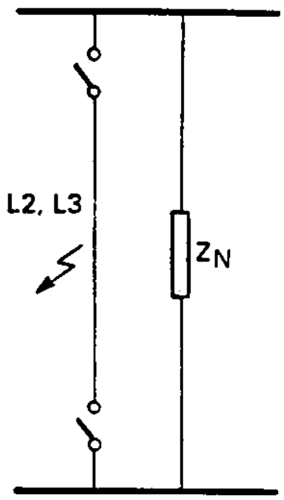
If no synchronous check is used it can be dangerous to use three pole reclosing very close to large power stations. In the case of maloperation the machine can be without any connection to the network during the dead interval. Later when the circuit breakers close again the generator can be out of synchronism with the network.

The advantage of this scheme compared with single pole is the simplicity of protection and auxiliary circuits. There is no unsymmetrical situation during the dead interval. From the stability point of view this system can be a disadvantage compared with a single pole reclosing system.



The two healthy phases keep the synchronism during the interruption time. The unbalanced situation creates negative and zero sequence currents in the network.

Fig 8:2 Single pole reclosing



Z_N = Transfer impedance. Small enough to keep synchronism during the interruption time.

Fig 8:3 Three pole reclosing

8.4 Delayed reclosing

Normally all high speed reclosing is performed only with one attempt. In the case of a sustained fault all three phases are opened and locked out.

Very often single pole reclosing equipment has an extra device delayed reclosing. - This means that in case of unsuccessful high-speed reclosing, there will be a second attempt. After some seconds the power line will be energized from one end and synchronized in the other end. The reclosing is very slow and cannot be of any help for the stability in the transient situation.

8.5 Automatic restoration

Some countries use more sophisticated automatic restoration. The equipment operates on all circuit breakers in the station. In the case of a black-out, it will, as soon as voltage appears on a line or a busbar, automatically close circuit breakers in a certain order until the whole station is restored. The automatic control can be started or stopped from the operating center. However "automatic restoration" is a local equipment and can be considered as a redundant system with reference to a remote control system.

9. PROTECTION SYSTEMS USING TELECOMMUNICATION

9.1 General

As already mentioned in chapter 6, it is important for stability and selectivity reasons to ensure fast and almost simultaneous tripping for all fault locations on the protected transmission line. In order to reduce material damage, avoid shaft damage to large thermal units and make it possible to use high speed reclosing it is also of importance to have almost instantanous tripping for all fault locations. To achieve this it is necessary to use teleprotection systems in the protection system.

In general it can be said that all protection systems using teleprotection systems consist of the following subsystems shown in fig 9:1

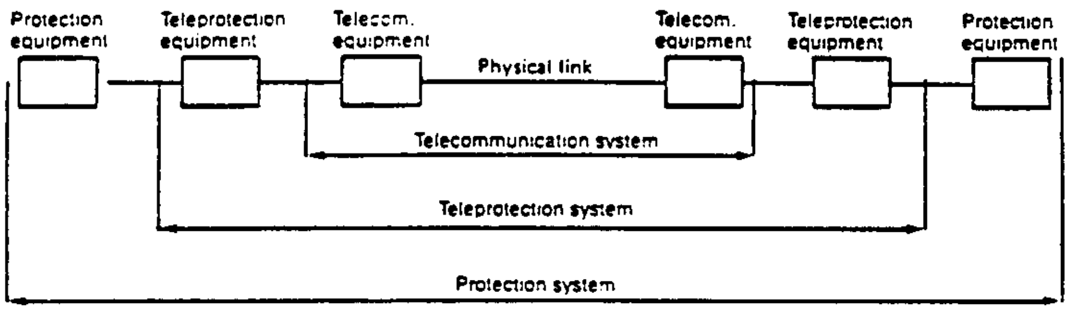


Fig 9:1 Protection system using telecommunication

9.2 Protection systems

Protection systems can be classified according to the type of information they transmit. They can be analogue or command protection systems.

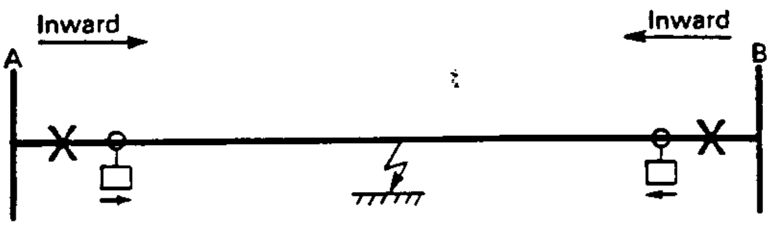
In an analogue protection system the information is transmitted by the telecommunication system in analogue or digital form. An analogue protection system is often an absolute selective protection. The analogue data is processed at each end of the power line and compared to the local values to determine if there is an internal or external fault. The comparison is carried out between instantaneous values of the power line quantities.

In a command protection system the information is a command signal which is transmitted by the telecommunication system. A command protection system is often based on a relatively selective protection.

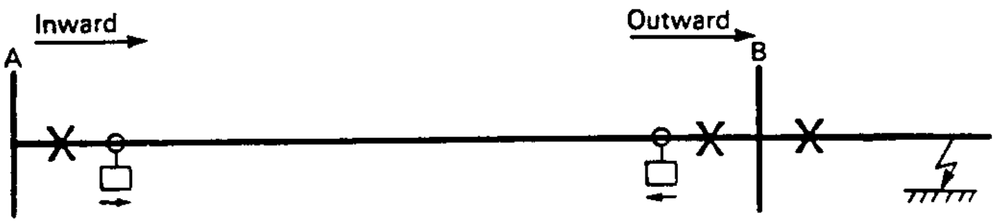
There are two basic methods of using simple command signals in a protection system, namely to give a command "to trip" (permissive or direct) or to give a command "not to trip" i.e. to block.

In permissive schemes a command is sent from one end by the protection which detects the fault. At the receiving end tripping is made dependent on the conditions of protection operations at this end.

In blocking schemes command signals are sent to the opposite end at external faults, to block tripping at the remote end. The decision whether the fault is internal or external to the power line protected is usually made by either phase comparison protections or distance protection alone or in combination with additional underimpedance protection. The principle of operation of this protection is shown in fig 9:2.



No command transmission: No blocking



Blocking command transmitted from B to A: No tripping

Fig 9:2 Basic principle of a blocking scheme based on current direction

In a blocking scheme, when power line carrier is used as telecommunication system, the signal is usually sent over a healthy line. In a permissive scheme normally the signal is normally sent over a faulty line. For that reason the blocking scheme usually gives higher dependability compared with a permissive scheme as far as signalling is concerned.

A combination of the permissive and blocking schemes known as "Deblocking schemes" in which a failure of telecommunication channel automatically simulates a received command signal for a limited period of time has also been used in command systems.

In an intertripping scheme there are no additional criteria from the protection equipment at the receiving end. These schemes also belong to the command protection systems and can sometimes be used instead of the schemes mentioned above.

9.3 Teleprotection systems

The requirements of the teleprotection system in the total protection system differ from application to application. There will not be the same requirements for e.g. an inter-tripping scheme as for a permissive scheme. Sometimes high security can be preferred high dependability and in other cases just the opposite.

The most significant parameters of a teleprotection system are:

- Transmission time
- Bandwidth used for the transmission
- Signal to noise ratio at the receiver input
- Security and dependability

In principle the user of a teleprotection system wants

- Short transmission time
- High security
- High dependability
- Low transmission power
- Narrow bandwidth

It becomes evident that all these requirements cannot be fulfilled at the same time and that the logical outcome is to establish an adequate relationship between all the different parameters bearing in mind the use to be made of the given teleprotection system and carefully weighting the effects of the errors and tolerances that necessarily will exist in a real system.

Very short transmission time implies that the bandwidth for the teleprotection channel has to be large (this means that the receiver will be influenced by more noise), and the decision time or processing time of the received signal has to be short. Both parameters imply less reliability.

When longer transmission times are permitted the situation evolves towards the need for less transmission bandwidth, improving the signal-to-noise ratio, having more decision time at the receiver, which in turn implies the reduction of the number of errors, therefore increasing the overall system performance.

Clearly, then unless the transmission channel is nearly noise free, in most cases, the transmission time chosen has to be as long as possible within the limits which are imposed by the protection scheme being used.

Summing up a protection system must be co-ordinated in all parts, each partial system matching the required specifications for the proper performance of the system. The provision of higher standards than those needed implies an increase in the costs of the partial systems, in other words, an uneconomical investment. Conversely, the use of telecommunication systems and equipment which do not attain the degree of specification required, can result in an inadequate protection system.

9.4 Telecommunication systems

The telecommunication system (media) can be pilot wires, power line carrier, microwaves or optical fibres. These will be described in more detail in the following chapters.

Usually a telecommunication signal will not trip a circuit breaker without any criteria from the protection. Intertripping schemes are an exception. Consequently, false signals are sent during normal conditions on the power system will have no influence on the security of the protection system. However, if false signals are sent during a fault on the network and the protection criteria are fulfilled, this can result in an unwanted operation of the protection system. A power line carrier link is susceptible to faults occuring on the network. For that reason it is very important to take precautions against false signals in order to avoid unwanted tripping when this telecommunication system is used.

The dependability of sending a signal through a fault when the fault is a three-phase fault and is situated very close to the station is another important case to be taken into consideration.

10 PROTECTION SYSTEMS USING TELECOMMUNICATION ANALOGUE PROTECTION SYSTEMS

10.1 General

Analogue protection systems are based on the transmission of analogue information about primary quantities such as amplitude and/or phase. This information can be transmitted in either analogue or digital form.

Analogue protection systems are usually absolutely selective protections. In order to get back-up for external faults, a relatively selective protection is usually added to the analogue protection in order to achieve a complete power line protection system.

10.2 Mixing and segregated techniques

10.2.1 General

Analogue protection systems can be divided into two groups. One is called segregated protection and the other non-segregated protection. The latter use mixing equipment. The mixing equipment can be a mixing transformer or a phase sequence network.

The basic principle of a protection system using mixing equipment is to mix the values of the three power phases into one phase value and one protection equipment can be common to all three power phases (non-segregated).

A segregated analogue protection system consists of one protection equipment for each phase. This system is more costly than the first mentioned. It has advantages for single-pole reclosing and for high resistance faults. Consequently this kind of protection does not need any mixing transformer.

10.2.2 Mixing current transformers (Summation transformers)

The mixing transformer produces a single-phase alternating current by geometric (vector) summation of the three-phase currents. The output current varies with the type of fault and consequently, sensitivity varies with each type of fault. The mixing transformer on the input side has to be designed in such a way that all kind of faults including three-phase faults will give a sufficiently large secondary current output.

The three primary windings of the mixing transformer shown in fig. 10:1 have the relationship 2:1:3. The highest sensitivity is obtained at earth faults. This suits many practical applications where primary earth fault currents are often less than those for phase to phase faults.

Other ratios than those mentioned in fig. 10.1 can be used. The transformation ratio may be chosen to make the matching between relay equipment, telecommunication system and current transformers more favourable. The transformer may also provide the necessary galvanic separation between these circuits. Mixing transformers are usually used in longitudinal differential protection systems.

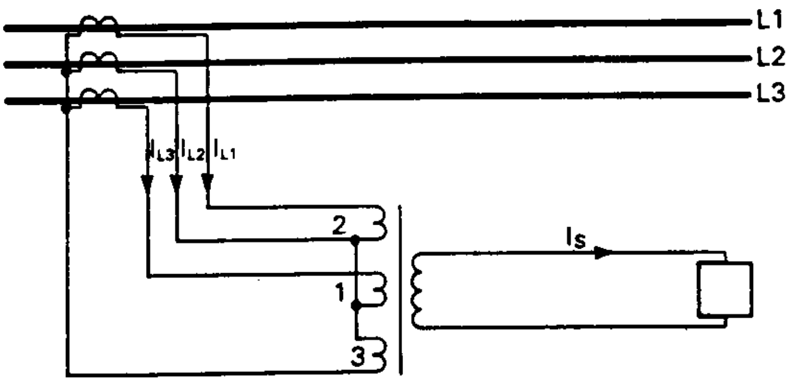


Fig 10:1 Mixing current transformer

10.2.3 Phase sequence networks

The phase sequence network is similar to the mixing transformer, so it is also used to provide a single phase quantity output proportional to the primary polyphase quantities.

The single phase output is proportional to the positive, negative and zero sequence input. Sensitivity to the different types of faults depends on the weighting factors of the different components designed into the sequence current network.

The negative sequence component exists in all kinds of power system faults except in the case of three phase faults.

The combination of sequence components to produce a modulating signal varies from a mixture of positive and negative sequence current ($I_1 + kI_2$) to the more generalized form comprising all components ($I_1+kI_2+k_oI_o$). The typical values of k and k_o are the values of k ranging from 4 to 10 in (I_1+kI_2), and in the second case normally k=3 and k_o=5.

In most cases filters are used in the input current circuits, in order to suppress as much as possible the DC transient component of current and remove the high-frequency current occurring during line charging or energizing of transformers or power lines. A phase sequence network is usually used for phase comparison protection systems.

10.3 Longitudinal (current) differential protection systems

10.3.1 General

The longitudinal differential protection is an absolutely selective protection system often used for cables and overhead lines at all voltage levels and for any type of power system neutral arrangement. This protection system is particularly suitable where

- the possible settings of the distance protection are not adequate to cover short lines and cables

- a redundant protection system is to be introduced in accordance with chapter 7
- only current transformers and no voltage transformers are available at each end of the line.

Starting relays are required in cases where the telecommunication system is not continuously available for selective protection. This may occur when the telecommunication system is normally connected to supervision or communication for other purposes.

10.3.2 Basic principles

Differential protection is based on the principle of current magnitude and phase comparison and is therefore also called current comparison protection.

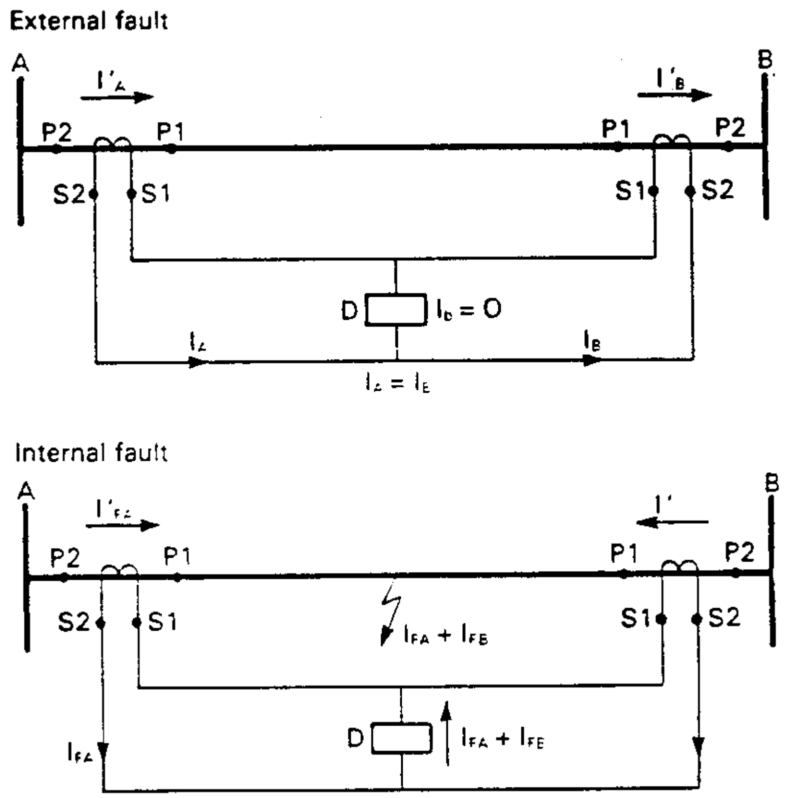


Fig 10.2 Basic principle of differential protection

The secondary windings of the current transformers can, with identical transformation ratios, be so connected together that they form a closed circuit for the secondary currents. The relay D shunted across the wires is energized in accordance with the algebraic sum of the primary currents at the terminals and carries no current under normal conditions.

For a fault inside the zone limited by the current transformers, however, the relay receives a current $I_{FA}+I_{FB}$ proportional to the sum of the fault currents $I'_{FA}+I'_{FB}$

flowing in from each side. The simple arrangement according to fig 10.2 therefore leads to operation of this relay for a short circuit inside the protected area. In the case of an external fault with very large current flows through the protection and the relay D will receive a differential current if the current-transformers are in a saturated situation or the magnetizing characteristic are different. If this exceeds the operation level, tripping could occur. Such an unwanted tripping of the protection is prevented by the stabilizing features. The stabilizing effect is usually proportional to the through-current.

During undisturbed operation the currents at both ends of the protected zone are not exactly the same in magnitude and phase position. This is due to the capacitance of the three conductors. Particularly in cables, the capacitive charging current can attain significant values. Nevertheless, these capacitive currents usually remain within safe limits for the differential protection.

In special cases this phenomena can lead to an unselective tripping of the differential protection and compensating connections have to be introduced. The compensation is required only at one end.

It is recommended that identical types of current transformers be used at both ends of the line. It is not acceptable to use closed iron-core current transformers at one end of the line and linearized current transformers at the other end.

If linearized current transformers are available for the connection of the differential protection at both ends of the line, it is only necessary to ensure that the total connected burden is not greater than the rated burden of the current transformer.

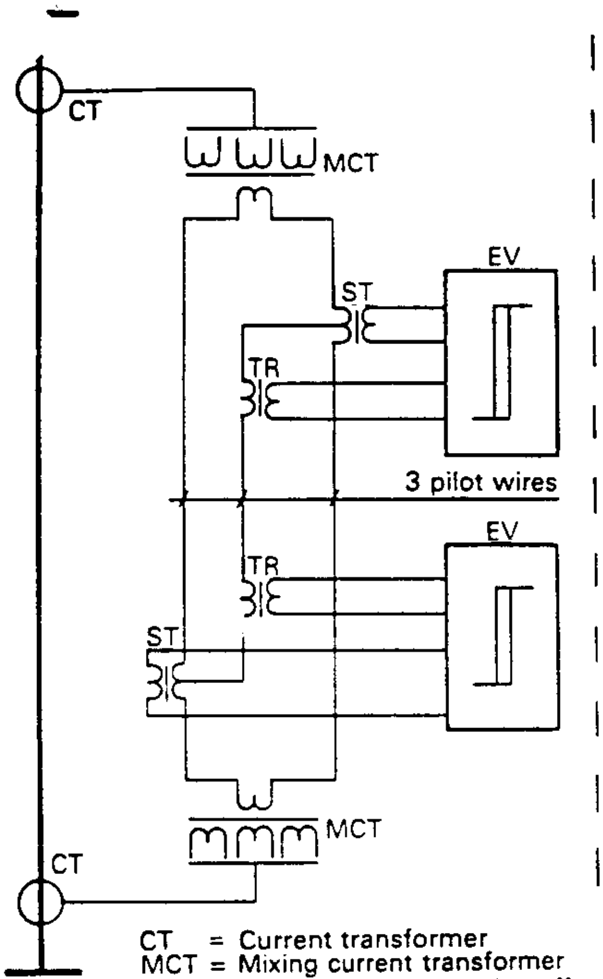
10.4 Longitudinal differential protection systems using pilot wires

10.4.1 Basic principles

In a differential protection system the information derived from the power system corresponds to both the amplitude and phase angle of the primary currents. These secondary quantities may be in the form of current signals or voltage signals which are proportional to the primary current. Accordingly there are two basic methods of creating a differential circuit, current balance or voltage balance, as shown in figs. 10:3 and 10:4.

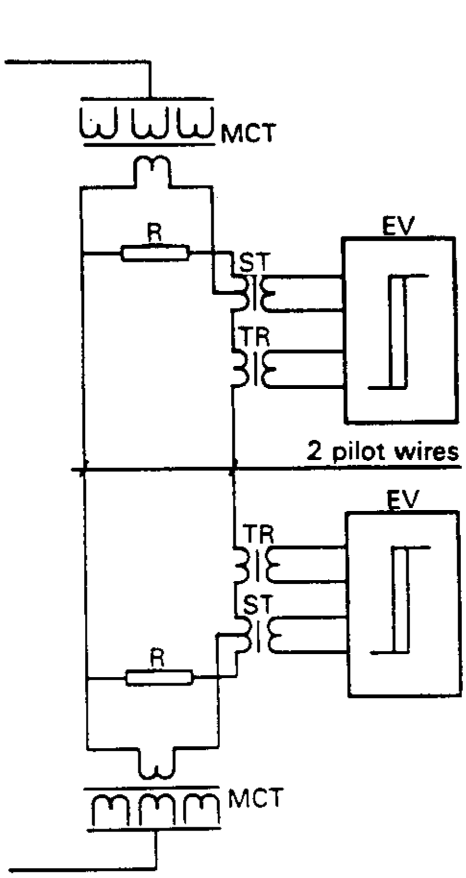
In both arrangements, the secondary currents of the current transformers at the two line ends are converted into proportional comparison values. If necessary, intermediate current transformers may be used to balance out any difference in the CT ratios at the two ends. For this purpose of comparison, the three-phase system is converted into a single AC current in the mixing transformer MCT (non-segregated).

One differential system for each power phase (segregated) of the protected circuit can also be provided, which gives a special advantage in networks with single pole reclosing. If high resistance faults are expected or faults on which the value of earth fault current is relatively low, a fourth measuring system for the zero sequence component can be introduced. This however, increases the number of pilot wires and therefore the transmission cost of the comparison information.



CT = Current transformer
MCT = Mixing current transformer
TR = Transformer for tripping effect

Fig 10:3
Basic scheme of a current-balanced system using 3 pilot wires (line-length up to about 8 km)



ST = Transformer for stabilizing effect
EV = Evaluation circuit

Fig 10:4
Basic scheme of a voltage-balanced system using 2 pilot wires (line-length up to about 25 km)

To achieve the above mentioned current balance system as shown in fig. 10:3, three pilot wires are required between the stations for interconnecting the two relay-units. The units of the voltage balanced system in fig. 10:4 are connected via a pair of pilot wires; but there are other voltage balanced schemes requiring three pilot wires.

In both methods, a replica of the vector difference is formed at each line end by means of a transformer ST for the stabilizing effect and a replica of the vector sum of the currents flowing at each end by means of a further transformer TR for the tripping effect. These values are evaluated separately at each line end in a measuring module and a tripping command is issued to the circuit-breaker when the fault current has exceeded a permanently adjusted threshold value. The measuring circuit which evaluates the stabilizing and tripping values has to be so dimensioned, that the differential relay does not operate on faults occuring outside the protection zone, even in the event of CT errors up to a certain value.

The I_{FA}/I_{FB} diagram of fig 10:5 shows the tripping characteristic of a typical longitudinal differential protection. The currents I_{FA} and I_{FB} (positive current direction at either end from the busbars into the line) are marked on the co-ordinate axes. During normal operation $I_{FA} = -I_{FB}$. This condition is indicated by the dot-dash line inclined at 45°.

The two operating characteristics of a differential protection which separate the tripping area from the blocking area are arranged symmetrically to this dash-dot line.

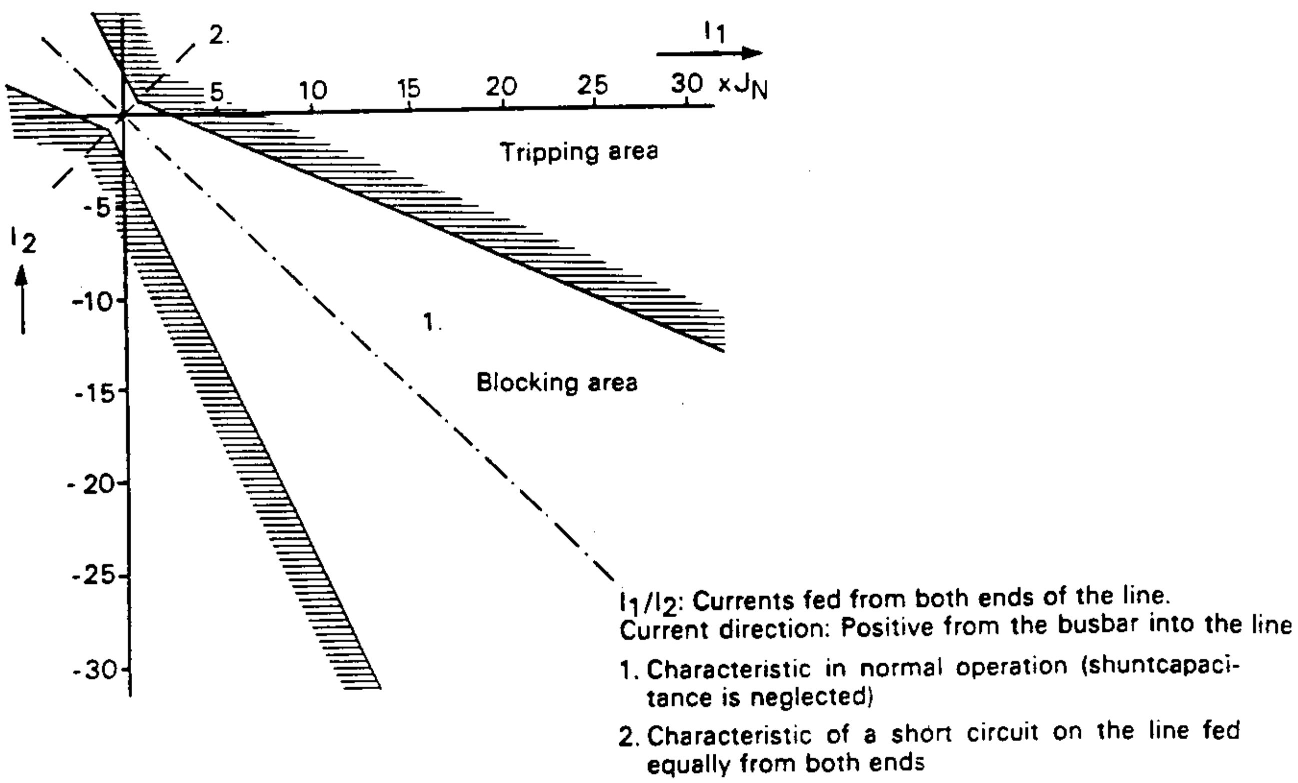


Fig 10:5 Typical characteristic of a longitudinal differential protection

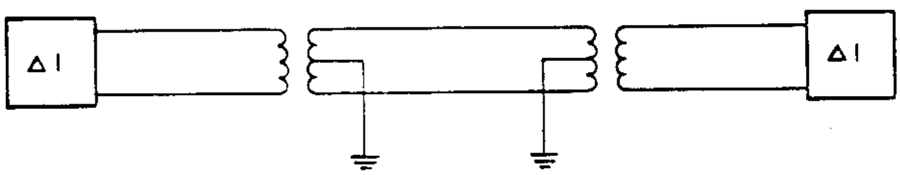
10.4.2 Compensation for pilot cable capacitance

Due to the capacitance of pilot wires the differential protection may operate for large through fault currents. This influence depends on the electrical characteristics and length of the interconnecting pilot wires. Within certain limits of these, it is possible to use relatively simple forms of differential protection as described, in which the selectivity and sensitivity are adequate and substantially independent of the particular parameters of the pilot wires. In other cases, where the length or type of pilot wire precludes this simple approach, for example, pilot wires more than 20 km, additional features are generally necessary which compensate for the effects of the pilot wires. The ability of the protection to select between internal and external fault conditions will then improve.

10.4.3 Immunity to high induced voltages

The pilot wires must be able to do their duty during a short-circuit. For this reason a high voltage test is required so that they can withstand the voltages induced into the cable during an earth fault. In cases where higher voltages are likely, the protective relays should be isolated from the pilot wires by isolating transformers.

Isolating transformers can also be used to subdivide the total length of the pilot wires into two or three sections. This prevents the equipment from being subjected to excessive longitudinal voltages due to interference. In any case the grounding conditions should be considered.



ΔI = Longitudinal differential protection

Fig 10:6 Use of isolating transformers for pilot wires

The applicable safety regulations must be carefully observed during planning, installation and maintenance. For the purpose of protection systems, it is not admissible to apply surge arrestors for the reduction of high induced voltages.

10.4.4 Pilot wire monitoring

The pilot wires form an important part of the longitudinal differential protection and their healthy condition is a prerequisite for proper operation of the protection. The protection system has to be monitored continuously for interruption and short circuit.

10.5 Longitudinal (current) differential protection systems using modulation technics

10.5.1 General

Longitudinal differential protection systems using pilot wires were described in chapter 10:4 . This protection cannot be used for long power lines. Normally it is restricted to 10-25 km depending upon the scheme used.

Longitudinal differential protection systems using modulation techniques can be used for all power lines regardless of length. The telecommunication system will be fibre optic power line carrier or micro waves instead of pilot wires.

In these systems, instantaneous current values at each terminal are transmitted to the other terminals by a telecommunication system.

There are two modulation methods for transmitting instantaneous current data to the remote terminals. They are called

- Frequency Modulation (FM) differential protection systems
- Pulse Code Modulation (PCM) differential protection systems

10.5.2 FM (current) differential protection systems

In the FM-system instantaneous current-values at each terminal are transmitted as analogue quantities to the other terminals in a voice frequency band by frequency modulation. In each terminal evaluation takes place based on the current differential principle. The principle of the protection is shown in fig 10:7.

The instantaneous current value is modulated in the 0.3 to 3.4 kHz frequency range of so that it can be included in a voice channel as shown in fig 10:8. Fig 10:9 shows an example where voice channels are used for segregated current differential protection systems.

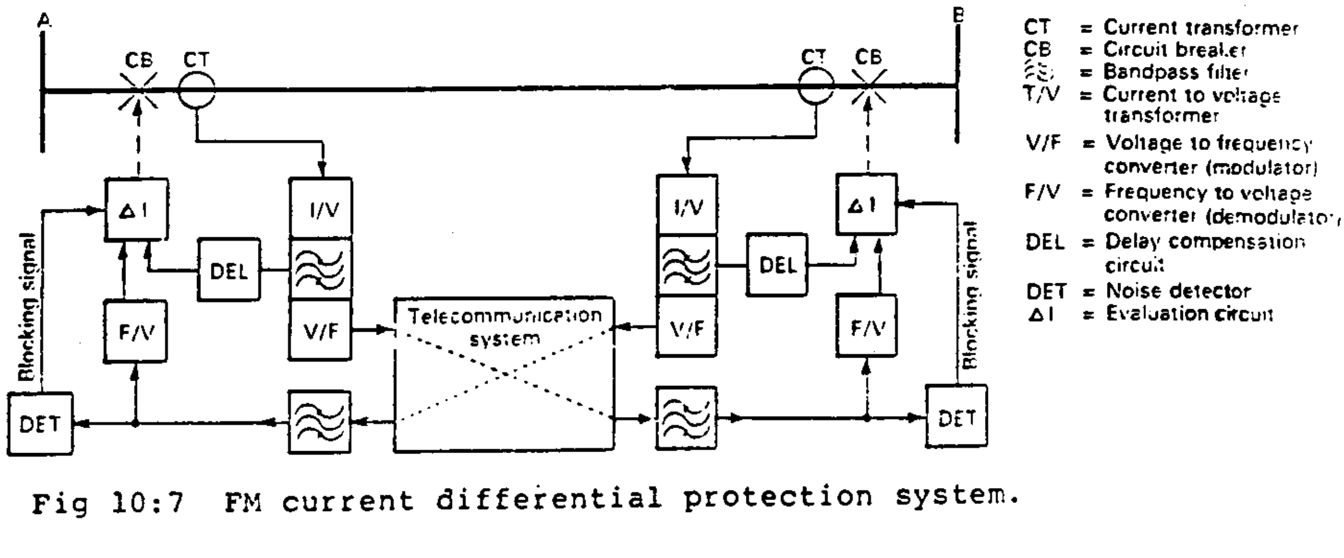


Fig 10:7 FM current differential protection system.

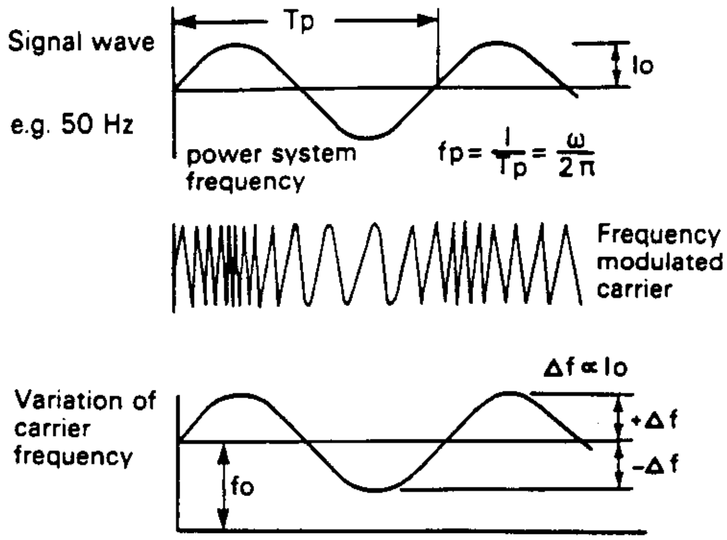


Fig 10:8 Signal wave and carrier of a FM current differential protection system

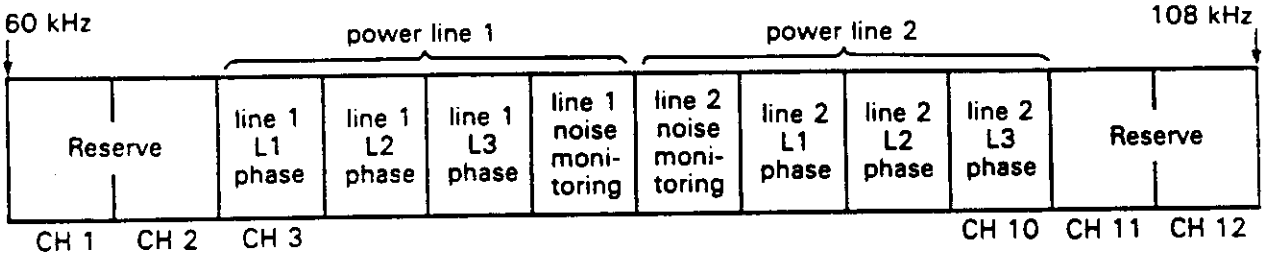


Fig 10:9 Example of a channel arrangement for segregated FM current differential protection systems for a double circuit power line

10.5.3 PCM (current) differential protection system

In the PCM system instantaneous current values at each terminal of the power line are sampled and transmitted toward the other terminals by pulse code modulation of the transmitted signal. Fig 10:10 shows the basic principle of this protection.

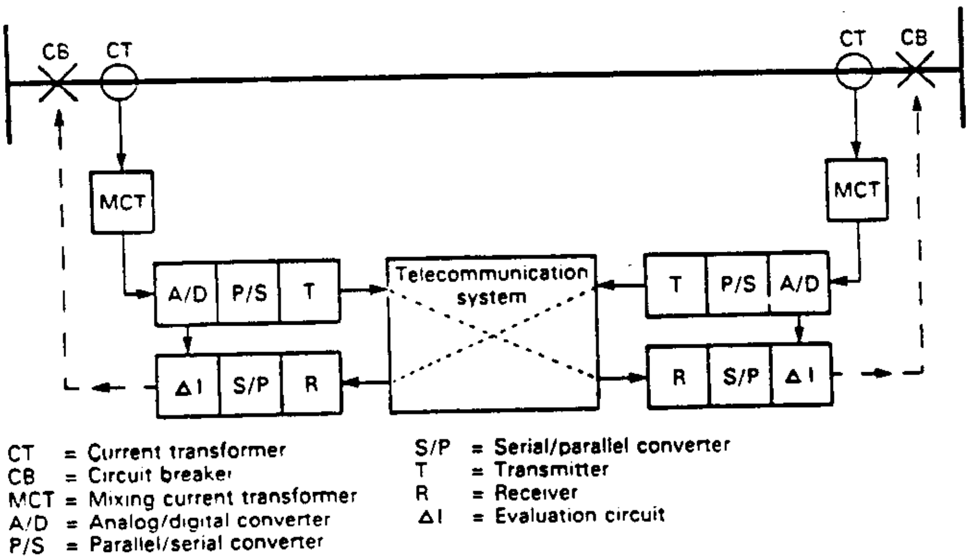


Fig 10:10 Example of a non-segregated PCM current differential protection system.

The analogue primary current is transformed by the CT and the secondary current is fed to a mixing transformer MCT. A quantity proportional to the primary current is obtained for current comparison. This signal is brought into the data terminal device, where analogue to digital conversion takes place in the A/D-converter.

In a segregated PCM differential protection system, the analogue-digitalconversion has to take place for each phase.

The sample and ranging have to take into consideration the characteristics of the measurement, as well as the requirements on the transmission system and the available transmission capacity (bandwidth). Sample rates ranging from 12-60 times cycle have been used.

The digital data are transmitted serially to the opposite terminal by the telecommunication system via micro-wave or fibre links.

In station B, the received signals are reconverted into parallel data. The evaluation circuit, e.g. a microprocessor-based computer, compares the currents of both terminals according to amplitude and phase angle. To simplify the evaluation, synchron of sampling can be used at each terminal of the line.

The technical implementation of this system is symmetrically arranged and the measuring quantities from B are transmitted to A, where the same current differential protection device is installed.

It is also possible to carry out the current comparison by an analogue evaluation circuit. Then the parallel data at the receiving end is converted into an analogue quantity and to compared with the local values.

If the transmission system or the data terminal device itself is faulty or out of service, the line differential protection must be blocked.

The received signals are monitored continuously by a noise detector which can block the longitudinal differential protection system.

10.6 Phase comparison protection systems

10.6.1 General

The phase comparison protection system, already mentioned under chapter 6, is normally used on high voltage and extra high voltage power transmission lines. It is an absolutely selective protection system and it is also classified as an analogue protection system.

A phase comparison device measures at each end of the power line the phase-angle between the current in the near end and the current in the remote end. If the angle is small it is an external fault or just normal load transportation. If the angle is large it is an internal fault. To be able to compare measured values it is necessary to use a telecommunication system. The most common telecommunication media is power line carrier (PLC), but radio-links, pilot wires and optical fibres are also used.

Since all phase comparison systems use current values only for fault location, they are not affected by system swings and out-of-step conditions. They are not influenced by zero sequence mutual induction of parallel lines. They have some advantages as protection systems for series compensated power lines. However if the capacitors cause negative direction of the short circuit current they cannot operate before the gap has been shorted by flash-over. Voltage transformers are not required or are used only when underimpedance protection are used as fault detectors. Normally this kind of protection is not affected by the problems of current reversal phenomena as often appear on parallel power lines and when distance protection is used.

The basic principle of all phase comparison is to measure the angle mentioned above. However, the method of doing so can differ from manufacturer to manufacturer. A phase comparison system can be characterized by the following features.

- Phase comparison equipment for each power phase. (including some zero sequence circuit) (Zero sequence circuit is included) Segregated protection.

- Phase comparison equipment common to all three power phases. Non-segregated protection.

- Phase comparison measuring twice every power period. Full-wave phase comparison.

- Phase comparison measuring once every power period. Half-wave comparison.

- Phase comparison with starter. The communication system will be modulated by the phase angle signal only when the starter has operated.

- Phase comparison without starter. Measuring is carried out continuously and the communication signals is permanently transmitted.

- Phase comparison can be designed in a blocking mode or in a deblocking mode similar to distance protection system using telecommunication.

Current which is used in the comparison is converted to a voltage. This voltage is converted to square wave - one for the positive half-wave and one for the negative half-wave. The square waves from the remote end are compared with those produced locally. Figs. 10:11 and Fig 10:12 show the principle.

The currents at both ends of the line during normal operation or for external faults do not make exactly the same angle with reference to a common voltage so there is a phase difference between the two currents during normal load or external faults due to the capacitance of the power line.

The protection system must take this in consideration so it will not trip for normal load or external faults.

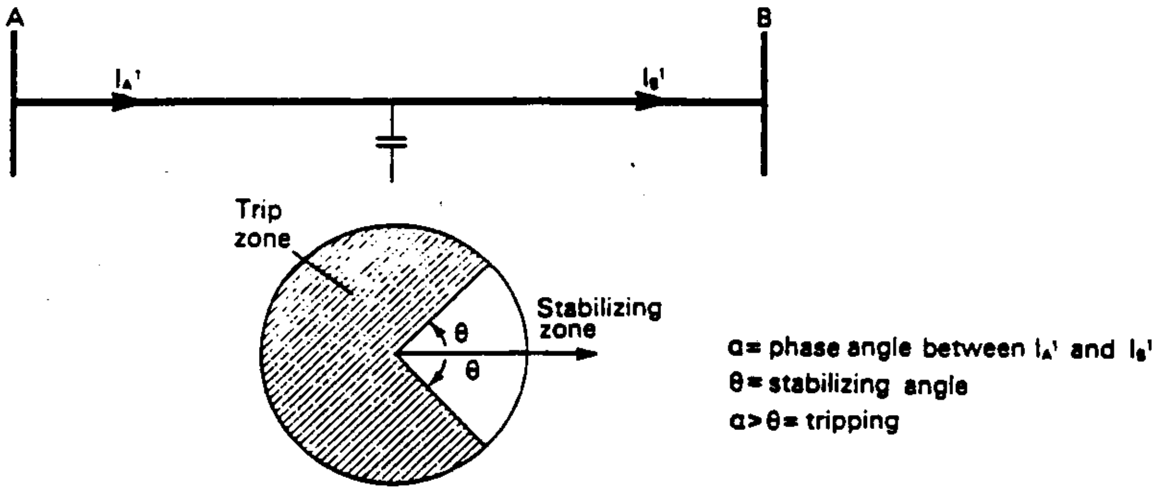


Fig 10:11 Stabilizing angle

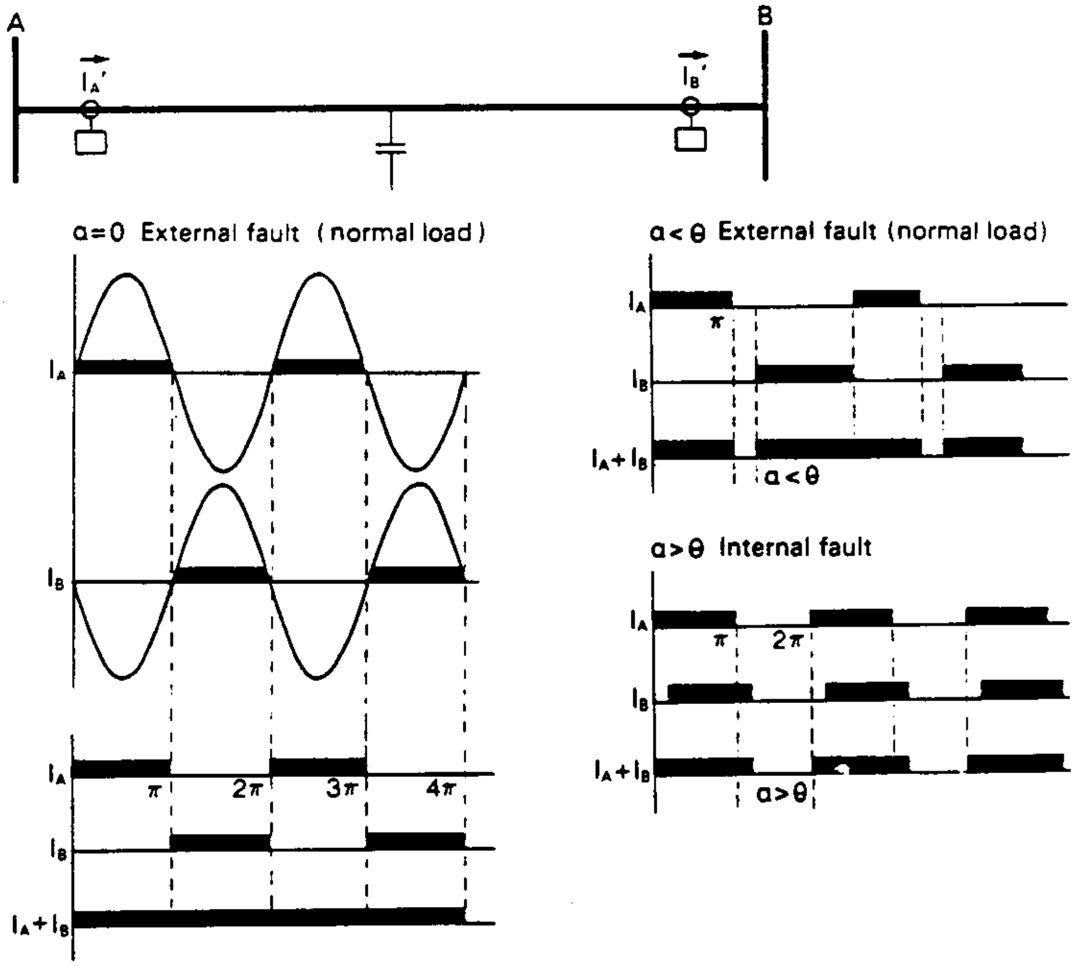


Fig 10:12 Half-wave phase comparison protection system

10.6.2 Non-segregated phase comparison protection systems

In the non-segregated phase comparison protection system, currents of the three power phases are mixed into one quantity by means of a composite sequence network described in section 10.2. A phase comparison with half-wave comparison and with a communication starter is shown in fig. 10:13.

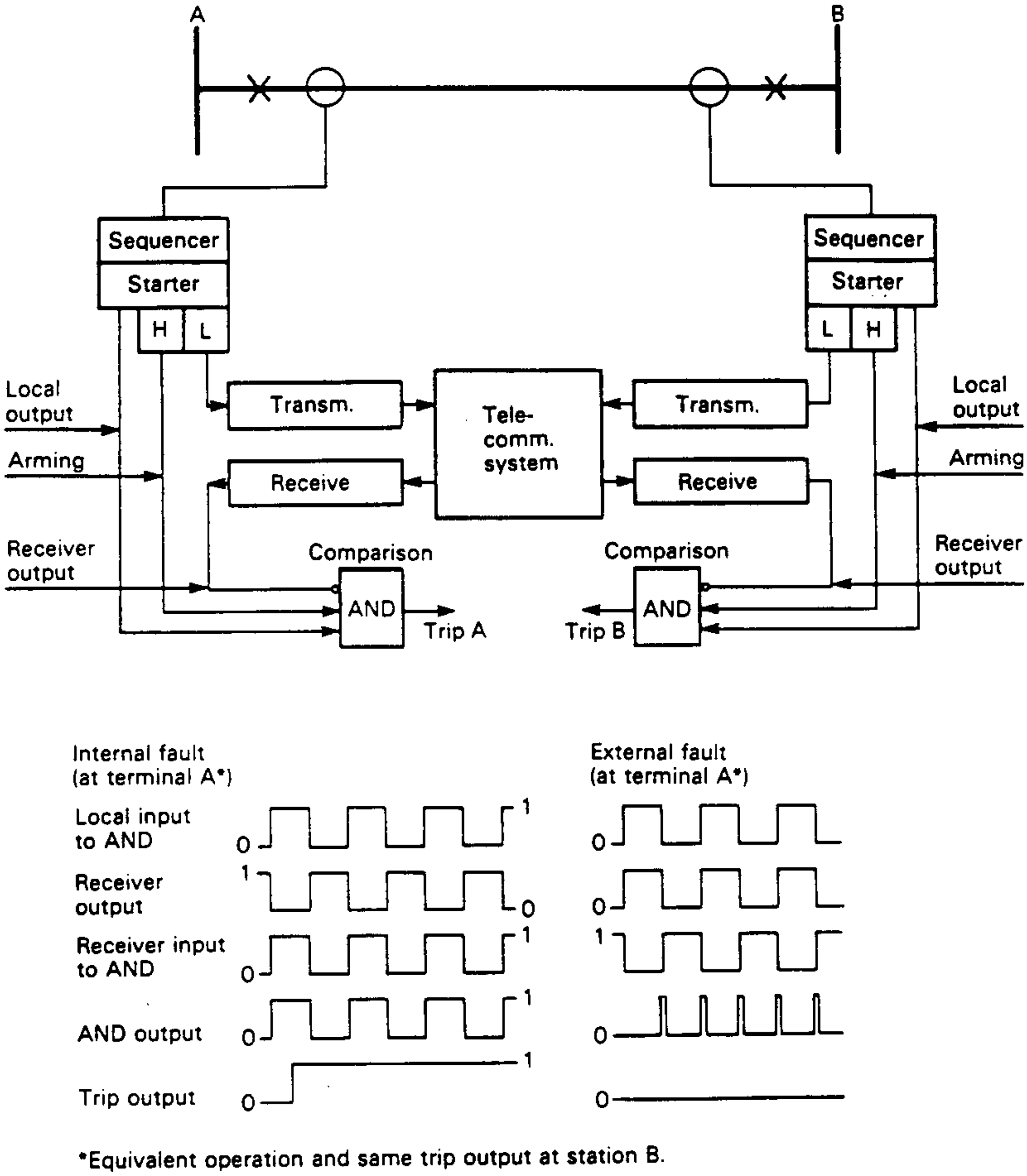


Fig 10:13 Non-segregated half wave phase comparison protection with starter

Starters are used to determine whether a fault has occurred and to supervise tripping. The systems, in other words, are permissive. The fault detectors must be overreaching - that is, set sensitively enough to operate for internal phase and earth faults required.

Since overcurrent fault detectors are normally used, voltage transformers are not required. Such a scheme is current dependent only. Fault detectors should be set above maximum load. On heavily loaded or long lines, it may not be possible to meet this criterion if a sensitive protection is required. Underimpedance fault detectors, which require voltage transformers, are used in such cases. Also zero and negative sequence current relays can be used as starter.

The start equipment in fig. 10.13 has two overcurrent relays L and H (low set and high set). L is the relay which starts the comparison and H provide a second criteria for tripping.

Normally the setting of the L-relay is of the same order or sometimes lower than the maximum load current. The relay H is set about 125-250 % of L. It is of importance to study different situations when setting these relays in order to achieve, as said before, a good sensitive protection system.

A full wave phase comparison system is shown in figs. 10:14 and 10:15. In this type the comparison is made twice every power period. Normally this protection is faster than the half-wave type. In the full wave system the telecommunication can be connected all the time to the comparison equipment and no starter is required.

For the half-wave comparison protection system it is possible to use power line carrier with the same frequency in both directions on-off amplitude mode. For full-wave comparison different frequencies for the two comparisons must be used.

10.6.3 Segregated phase comparison protection systems

The comparison in the segregated protection system is made in each phase separately from the other phases. It can be said that one protection is used for each power phase. Normally each phase also has its own communication system. Because of this phase-separation this protection system is very suitable for single pole reclosing, but it is more costly than non-segregated protection it is used on very important lines where selectivity and fast clearing times are important such as long EHV series capacitive-compensated transmission lines. Segregated phase comparison systems, which are current dependent only, are independent of the following phenomena:

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

The segregated phase comparison system can be divided int two types: a two-subsystem scheme and a three-subsystem scheme. In the two-subsystem scheme, one subsystem operates from the delta current (L_1-L_2) for all multiphase faults, and a ground ($3I_0$) current subsystem operates for all ground faults. The three-subsystem scheme has a subsystem for each phase (L_1 L_2 and L_3).

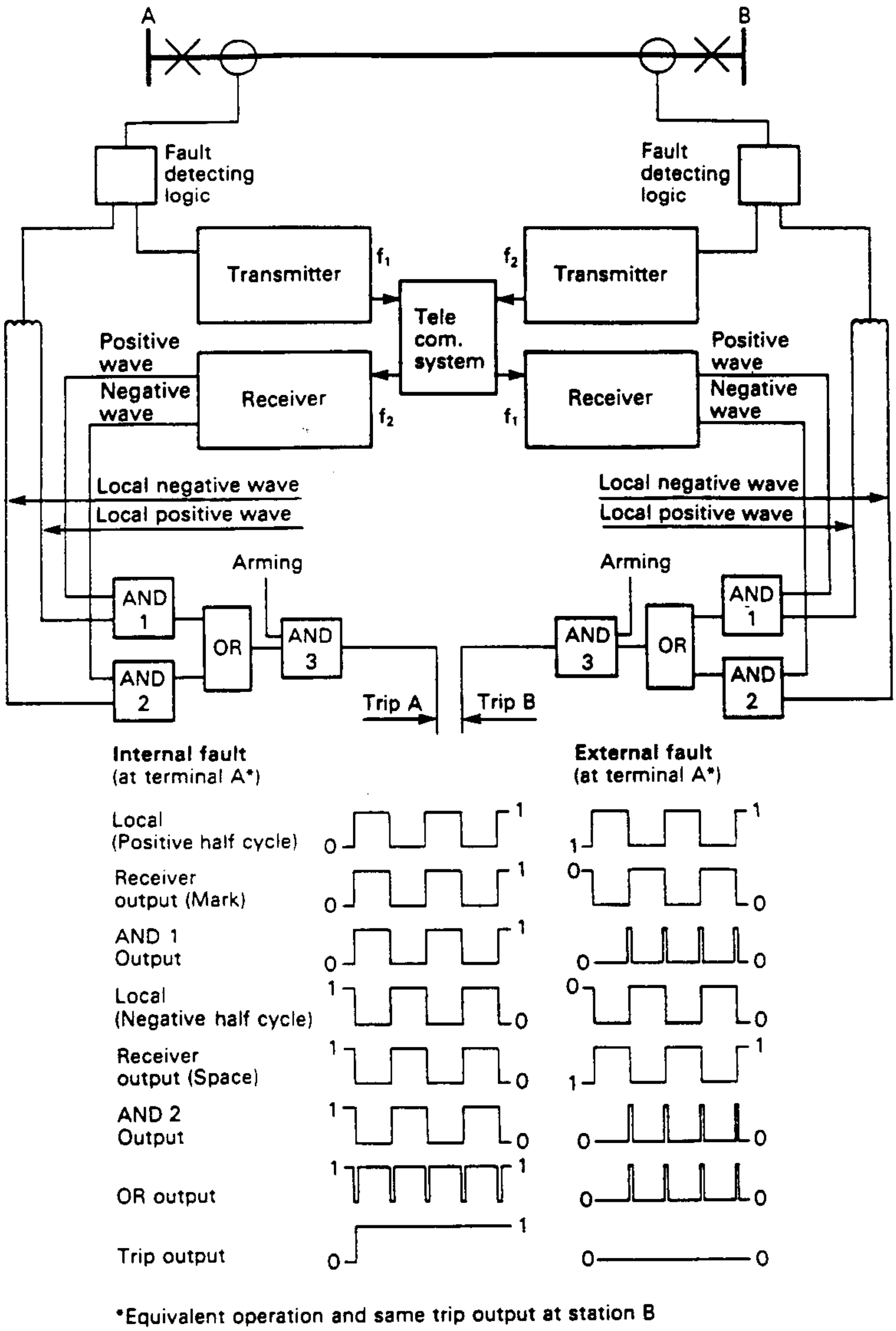


Fig 10:14 Non-segregated half wave phase comparison protection

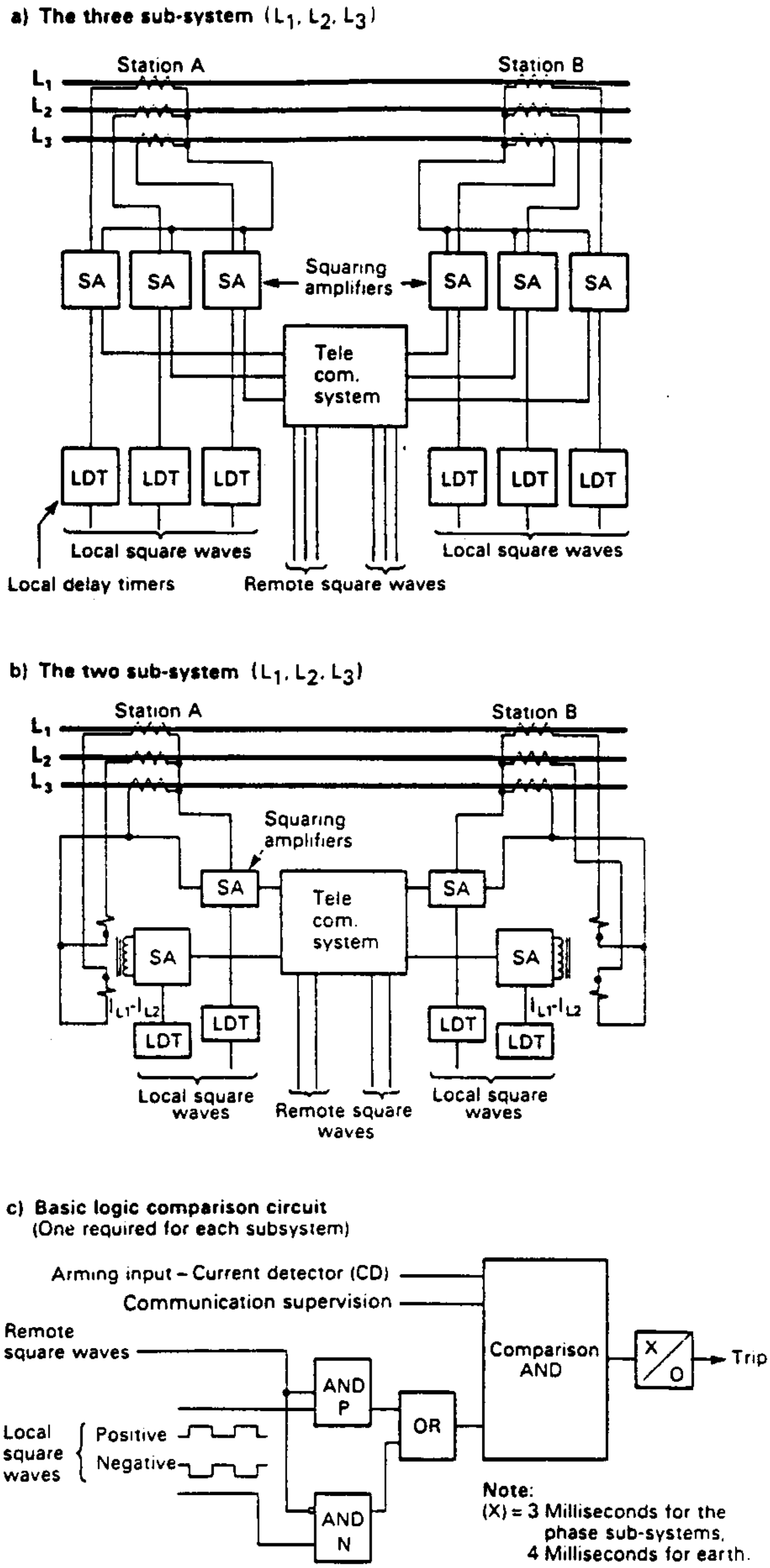


Fig 10:15 Segregated phase comparison protection system

Some applications permit the phase comparison protection to trip for internal faults with outfeed current out at one terminal. While the outfeed condition is very unusual, it presents difficult problems to the great majority of protection systems when it does occur. Outfeed can occur in any of the following cases.

- Series-compensated parallel power lines
- Weak-infeed or zero-feed applications
- Some multi-terminal applications
- Series-compensated power-lines with a source inductive reactance smaller than series capacitor reactance
- Some single-line-to-earth faults, occurring simultanously with an open conductor, where the fault is on one side of the open conductor

Normally in a half-wave comparison system an "on-off" power line carrier equipment is modulated by the square wave switched on during positive half-cycles, and off during negative half-cycles, or vice versa.

This teleprotection system might behave incorrectly in some situations due to noise created during a fault. For instance, in an internal fault at blocking mode protection the noise might simulate a transmission signal from the other end and block the protection equipment. For an external fault the noise might generate distortion at the receiving end, deblocking the protection equipment.

In a full wave teleprotection system, an FSK-frequency shift keying - signal modulates a telecommunication channel. The telecommunication system continuously monitors itself and when a fault occurs, the teleprotection equipment compares the local signal with the remote, doing this for both positive and negative half-cycles.

If the signal-to-noise ratio at the receiver is too low, the teleprotection system is blocked and gives an alarm. The use of a transmission system independent of the power line to be protected, will give the system better dependability. This type of teleprotection compares electrical magnitudes that occur at the same instant, which means the transmission time must be very short. In order to attain a good performance from the teleprotection system we must have a telecommunication system with a good signal to noise ratio, and little telegraph distortion.

In the segregated phase comparison the comparison is made in the same way as described above but for each phase. The transmitted signal may be digital or analogue. If an analogue transmission is used, the values of each phase are transmitted via independent channels, and in case of digital transmission, the values of each phase are transmitted in a series message form with a control code. This signifies that in order to compare instantaneous values, a high speed channel will be needed, somewhere around 48 kb/s (kilobit per second).

Normally, telecommunication systems used for these teleprotection are radio links or fibre optic links.

11 PROTECTION SYSTEMS USING TELECOMMUNICATION COMMAND PROTECTION SYSTEMS

11.1 General

As has already been mentioned in chapter 6 and chapter 9, a command protection system is usually based on a relatively selective protection system. The most common relatively selective protection used on transmission power lines is distance protection. In the following paragraphs therefore mostly telecommunication added distance protection systems will be described. Some command protection systems not using distance protection are described at the end of this chapter.

The first zone of a distance protection system is normally set to cover 80-90 % of the power line section to be protected. If no telecommunication facilities are used, high-speed simultaneous operation of the protections at both ends of the power line section can be achieved only for faults occurring between C-D of the transmission power lines shown in fig. 11:1. The faults outside this area, namely near both ends of the line, will be cleared sequentially. The protection nearest to the fault operating in its basic time, zone 1, will trip its circuit breaker while the other protection will operate in its second zone with time delay as shown in fig. 11:1.

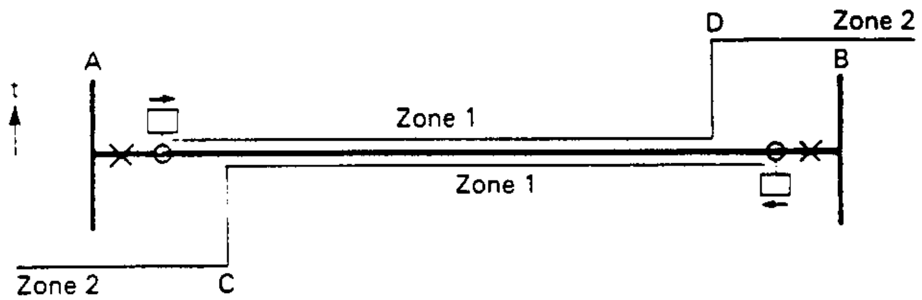


Fig 11:1 Normal setting of an underreach distance protection system

The use of a telecommunication system with a distance protection as discussed in this section and others, is to avoid delayed tripping in zone 2 for faults on the protected transmission power line. Over the years, different principles of application of the telecommunication signals to enhance the selective and rapid operation of distance protection for faults at all positions at the protected power line have been developed by different power utilities. The distance protection system using telecommunication can normally be divided into the following six principal categories.

11.2 Permissive underreach distance protection system

11.3 Intertripping underreach distance protection system

11.4 Accelerated underreach distance protection system

11.5 Permissive overreach distance protection system

11.6 Blocking overreach distance protection system

11.7 Deblocking overreach distance protection system

The different schemes, together with associated zone settings, permissive criteria and telecommand mode, are summarized in Table 11:1 at the end of this chapter. Depending upon the requirements of the systems, there are many variations and combinations of the six basic categories mentioned above.

In schemes of distance protection using telecommunication, normally the basic distance protection functions are there as a back-up to the zone operating with telecommunication system. In other words if there is communication failure the ordinary distance protection takes over. This means there is no need for an extra relatively selective protection as required with unit protection.

11.2 Permissive underreach distance protection systems

For a fault near the end A in fig 11:2 the protection in A operates and trips the circuit breaker at the local end. Simultaneously with the emission of the trip signal, a telecommand is sent to the opposite end.

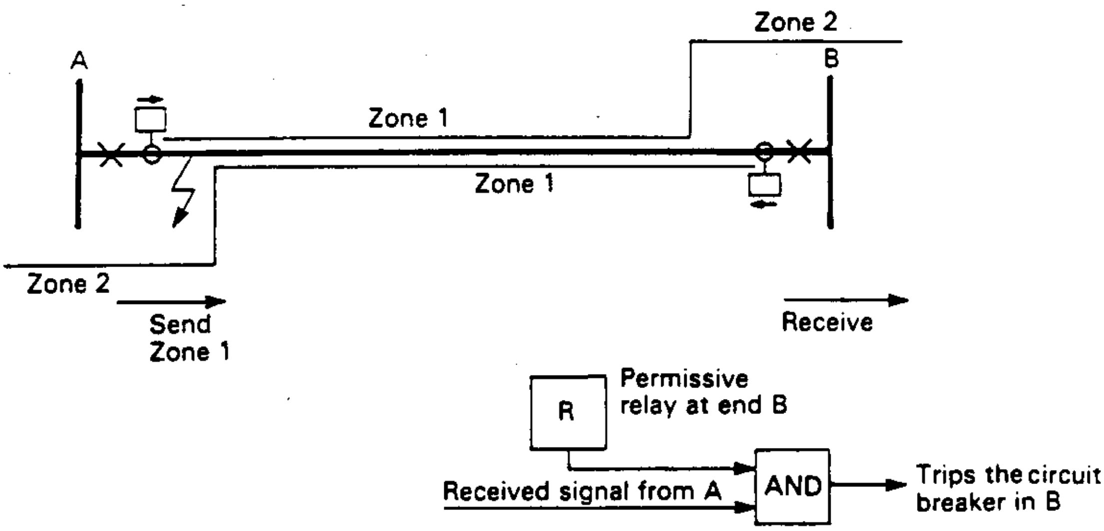


Fig 11:2 Permissive underreach distance protection system

At the receiving end the tripping is made dependent upon the fault detecting protection which can be of a different kind The most common are

- starters (zone 3) of distance protection
- directional or non directional underimpedance relay
- undervoltage relay
- overcurrent relay

This achieves a highspeed tripping time in comparison with the normal time delay of zone 2. For faults at the remote end the fault clearance time will be 15-40 ms longer than for a fault located near the protection due to the teleprotection time. In some cases, if no command is received, within a certain time after the starting relays function then the teleprotection is blocked.

Power line carrier (PLC) is often used as a telecommunication system in this protection scheme. To make the system highly dependable system the signal must be able to pass the fault location, particularly when the fault is located very near the sending end of the power line and when the fault is a three phase fault.

In order to have high security in the system the receiving end must not be sensitive to false signals coming from adjacent lines. These signals are usually generated in the instant of faults occurring and of operation of circuit breaker and isolators. Because of the overreach of the permissive device such a false signal can lead to a non-selective tripping. In a double circuit power line a noise-signal will easily be transmitted from the faulty to the healthy power line due to the mutual coupling between the two circuits. Precautions must be taken against such non-selective tripping.

With microwave links interference is less significant and security is not generally a problem. The dependability can be influenced of fading topological and climatic conditions.

11.3 Intertripping underreach distance protection systems

This is a variation of the permissive underreach distance protection system. Zone 1 setting of the distance protection is the same as in 11.2. The basic difference is that at the receiving end the telecommand signal from the opposite end is used to trip the local circuit breaker directly without any other additional criterion. This method is called intertripping underreach distance protection system or non-permissive (direct) underreach distance protection. A typical scheme is shown in fig. 11:3

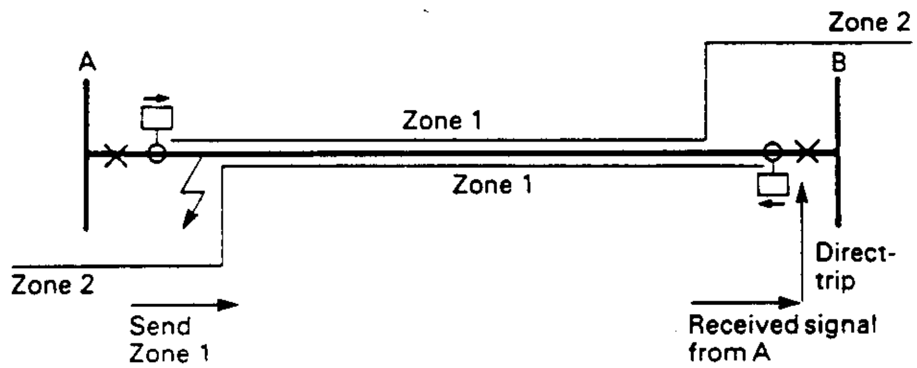


Fig 11:3 Intertripping underreach distance protection system

The received signal has complete ability to trip without any additional control and permissive criteria, and hence the reliability of the transmission signal is most important in order to avoid unwanted tripping. Means of improving the reliability in the presence of noise have special significance in this type of application. The probability of unwanted operation may increase considerably as the response time is reduced below 10-20 ms, so there is a need to assess the response time of the receiving device in relation to the overall operating time.

Dependability is important when power line carrier is used, because the command is transmitted during internal faults, when interference may be severe. The security of the signalling system has to be higher than for permissive underreach system.

For this purpose, all types of telecommunication links may be used, pilot wires being until now particularly common in some countries for short power lines of medium and high voltage power systems. Power line carrier is frequently applied to intertripping on longer circuits, particularly when it is used for other purposes as well. Fibre optic links will be increasingly applied.

Using pilot wires, simple systems of DC relays may be adequate for short lengths, for example up to 2..10 km, no special coding being necessary. Care may be required to avoid undue sensitivity of the receiver relays in relation to the energy stored in the shunt capacitance of the pilot wires. It is also generally necessary to adopt 2-pole switching for the pilot wires. For longer lengths of pilot wire a DC relay system may still be used, provided precautions are taken to avoid non-selective operation by induced voltages or by differences between earth potentials at the sending and the receiving ends.

Simple DC systems, even with the additional precautions mentioned above, are seldom adequate for telephone pilot wires, particularly when rented, and it is generally necessary to take special precautions.

In power line carrier intertripping schemes, the severe interference effects are especially important and merit consideration in applications of this type. Frequency shift systems are frequently used as they can provide fast overall operating times, for example about 20 ms, with adequate reliability in respect of both dependability and security. Sometimes combinations of two channels and timers are adopted. Coded frequency-shift channels are often applied. Overall operating times for protection systems needs to be less than 50..70 ms if an adequate improvement over the normal zone 2 back-up tripping time is to be achieved.

Intertripping over microwave links, interference is less significant, and security is not generally a problem. Reliability of equipment and the transmission path in relation to dependability becomes a more important feature of such applications. Sometimes a scheme employing 3 channels on the basis of a two-out-of-three solution is adopted.

11.4 Accelerated underreach distance protection systems

This scheme is similar to the permissive underreach schemes described in section 11.2 above. The difference lies in the use of the received signal. The received telecommand is used to increase the sensitivity of zone 1 of the distance protection by switching the zone 1 reach to cover more than 100 % of the line section, usually to about 130 %. It is called the acceleration zone - zone A - in a switched distance protection.

In cases where the full schemes of distance protection are used the incoming telecommand is used to override the time delay of zone 2. The fact that at the receiving end both the direction and distance are measured independently and used as a permissive criterion implies that this system is more secure than permissive underreach distance protection system.

Fig 11:4 shows the logic arrangement of such an accelerated distance protection system.

The acceleration scheme in which the basic zone is switched to extend beyond the basic transmission line protected is not quite as fast in operation as the other permissive underreach distance schemes, since time is required for the directional measuring unit to make a new measurement and operate after the range has been extended from zone 1 to zone A. However, when the security requirements to avoid a non-selective operation due to the receipt of a spurious signal is dominant, this scheme, although slightly slower than the other permissive schemes, is also safer from unwanted operation (increased security).

As in the case of a permissive underreach distance protection system, the teleprotection system especially when using PLC has to be judged upon its ability to pass a signal from one end to the other in spite of the additional attenuation introduced into the transmission path by the fault and the designed security not to transmit a spurious signal for faults external to the line. Reliability requirements on the teleprotection are about the same as for other permissive schemes, with the difference that the security requirements are slightly less severe.

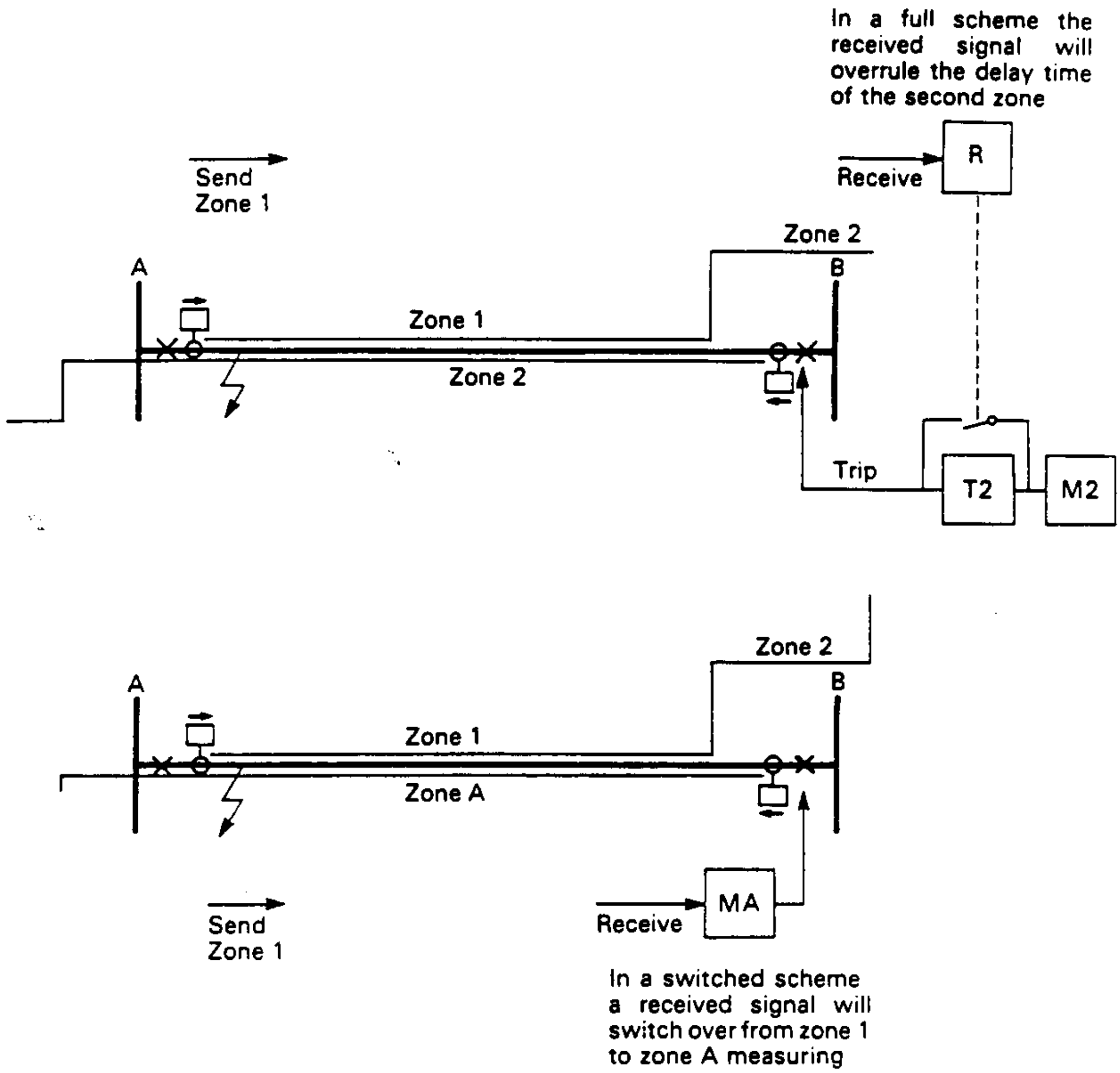


Fig 11:4 Accelerated distance protection system

11.5 Permissive overreach distance protection systems

This is another method of sending a trip command under internal fault conditions to the remote end to obtain high speed tripping with distance protection for all positions of internal faults. The reach of the zone A is normally set beyond the line protected, namely 120-150 % of the power line impedance. In this scheme zone A is not only a criterion for the receiving signal, it has also a sending task. For that reason zone A for a switched scheme is usually provided with a separate measuring unit to the ordinary distance protection.

In the case of full schemes the measuring unit of zone 2 will be used for this purpose. The principle is very similar to the direction comparison protection system described in section 11.8.

The zone A relays cannot be permitted to trip directly at high speed, and tripping at both ends is made dependent on both the operation of a zone A relay and the reception of a tripping (permissive) command from the remote end; in other words, tripping at each end depends on zone A relay operation at both ends.

It is clear that the correct operation of both the relays and the correct functioning of the teleprotection in both directions are necessary for complete isolation of a faulted circuit, and the teleprotection is thus an essential feature.

Fig 11:5 illustrates a typical method of application of such a permissive overreaching scheme, including the logic circuit.

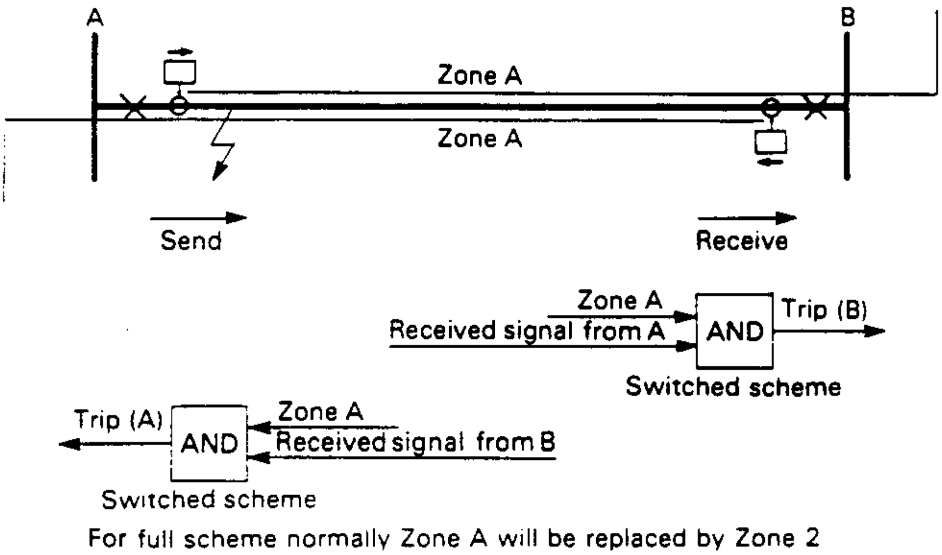


Fig. 11:5 Permissive overreach distance protection system

Very often permissive overreach schemes are used on short power lines. These cover fault resistance in a better way than the permissive underreach system. It is shown in fig. 11.6.

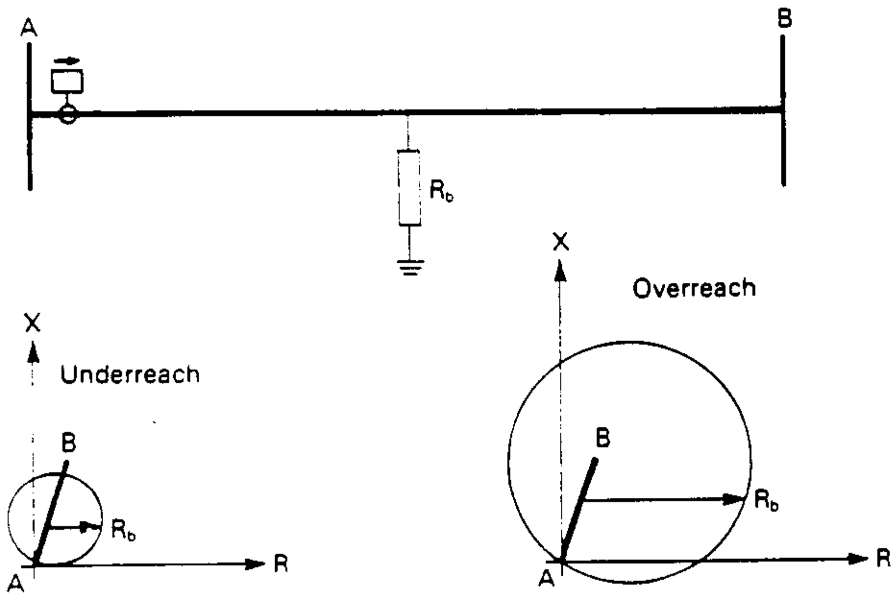


Fig 11:6 Permissive overreach on short lines.

It is also used on series compensated lines. Normally the first zone must be set less than X_L-X_C to avoid unselective tripping. X_L is the reactance of the power line and X_C is the reactance of the series capacitor. If there is a flash over at the airgap or if the series capacitor is out of service the reach of the first zone will be very short depending upon the compensation degree.

The sending relay will be set to 1,2 X_L to ensure that it will cover the whole power line when the series capacitor is out of service. When the series capacitor is in service the sending relay will have a high degree of overreach.

Risk of unselectively tripping when PLC is used is limited by the noise produced by a fault or switchgear operation just beyond the extremities of the power line protected. Teleprotection requirements are similar to those described under section 11.2 above.

During external fault conditions the receiver may operate because of excessive noise just outside the protected section, and false trips may occur if sufficient precautions are not taken.

The operating time of the protection system for all positions of faults on the protected line circuit includes the overall transmission time, and this should be relatively short, i.e. of the order of 15-30 ms or less, so that the band-width required could be greater than that for the permissive schemes mentioned under 11.2.

Pilot wires, radio, microwave or power line carrier links may be used provided they satisfy the requirements of high reliability and speed, and a frequency shift system will probably be used by all. In all cases the system would justify the provision of continuous supervision of the information link, because of its essential role in tripping.

The choice and application of distance protection for schemes involving permissive overreaching protection requires some care. For example, a fault close to one end will be tripped in a time dependent upon the operating time of the far end protection which may not be fast enough because the fault current at the remote end may be relatively low. Special arrangements to take into account the weak in-feed at the far end of the line protected, the problems of reversal of fault current direction following partial clearance of an external fault, an open-ended line, etc. have to be considered and special arrangements have to be made in order to be able to clear the fault under all conditions.

11.6 Blocking overreach distance protection system

As mentioned under section 11.5 - permissive overreach - the zone A of the distance protections is set overreaching to cover more than 100 % of the line with enough margin. Zone A together with a received signal will trip the circuit breaker.

In the blocking scheme a separate reverse looking element at each end will send a telecommand to the remote end to block the trip signal from zone A at that end in the case of faults external to the line protected.

Zone A of the distance protection has to be delayed a little to take into account the teleprotection time so that the telecommand can block the operation of the protection at the remote end successfully in the case of external faults. In a full scheme of distance protection zone 2 will replace zone A.

In order to ensure correct blocking for faults occuring outside the line section protected, it is necessary to let the separate reverse looking element have a reach greater than the reach set for the distance protection zone A. Fig. 11:7 and 11:8 show typical examples of a blocking scheme.

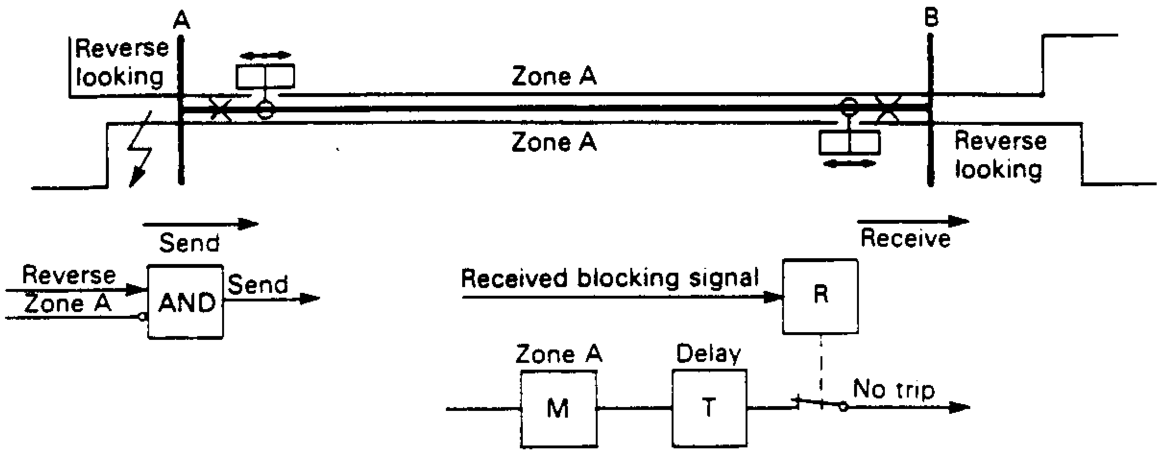


Fig. 11:7 Blocking overreach distance protection system
Typical arrangement with reverse looking impedance "or directional impedance" elements.

In some cases the extra reverse looking element can be replaced by a combination of the starter and the zone A element and thus no extra element is needed. The reach of the starter in the backward direction must be longer than overreach zone at the remote end.

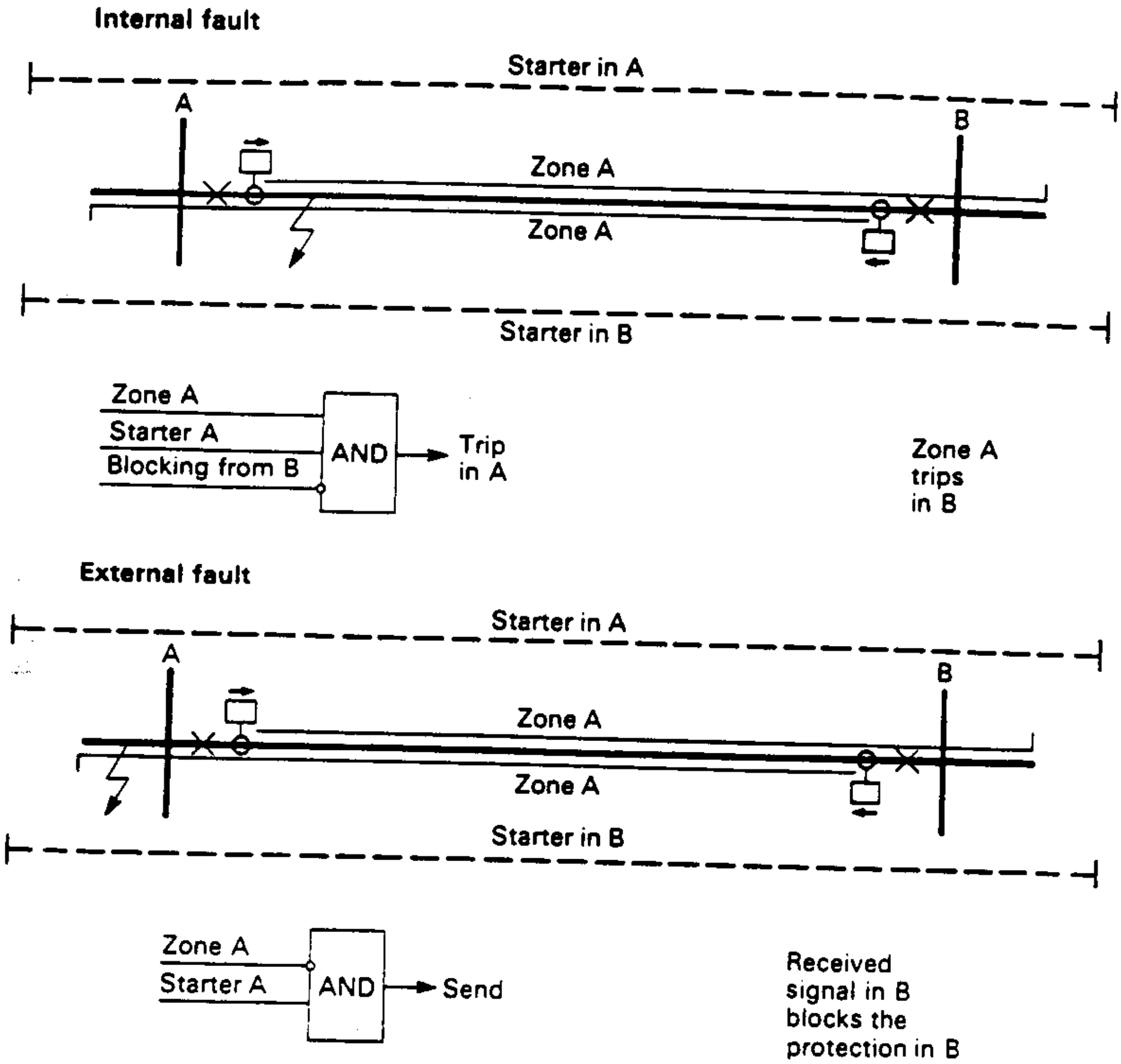


Fig 11:8. Typical arrangement of "Blocking overreach distance protection system" without reverse looking measuring element.

To obtain the correct blocking action on an external fault, the tripping action of the protection at the end feeding "inward" current must be delayed sufficiently to ensure that the command from the "outward" feeding end has been received. This delay must be kept to a minimum, and this means a fast channel and a fast overall transmission time. The general requirement for the teleprotection is that it should be both fast and reliable.

The transmission of the blocking telecommand is initiated by either the reverse looking elements or by nondirectional impedance elements, and is interrupted by the overreaching relay. Either one end or the other will transmit a blocking signal on external faults, and only on internal faults will there be no blocking signals. Depending upon the sensitivities of the non-directional impedance elements as well as the directional zone A elements, it is possible that in the case of internal faults, a transient blocking signal may be transmitted to the remote end in the case of internal faults occurring at positions where the zones of reverse looking and forward zone A elements overlap. In order to eliminate this disadvantage, directional distance protection as reverse looking elements can also be used. If the reverse looking elements are non-directional, then the "reset time" of the teleprotection (suppression of blocking signal at receiving end) must be very short. (No extension of the signal). The use of zone A settings in excess of the line impedance can be advantageous when applying this system to relatively short overhead lines (for example less than 30 km and pilot wires, when available, are particularly suitable for such applications.

In blocking systems the transmission of a command is not required in the case of an internal fault. Thus, internal faults that might delay or interrupt the telecommand are not a problem, and the additional attenuation normally introduced by the fault path need not be considered while defining the requirements of a power line carrier link as in the case of permissive systems mentioned under 11.2 and 11.4.

The use of teleprotection in a blocking sense avoids the problem of unwanted tripping due to interference, unless this can cause suppression of the true command. Even though interference during internal faults may cause a temporary delay in tripping, this is generally acceptable if this is not likely to exceed 10 ms. Thus, within their respective ranges of application, all forms of teleprotection may be used, provided they satisfy the requirements for speed and reliability.

Because of the possibility of a non-selective operation in the case of failure of the teleprotection, supervision features may be included to change the settings of the zone A relays to the normal 80..90 % of the protected circuit in such a case. In this case it is necessary to monitor the signals continuously both ways or to provide some form of automatic sophisticated self-checking facilities for the channels. However, for external faults within the reach of zone A unwanted tripping may occur if the telecommunication system fails or if the blocking signal is not received.

As in the case of all overreach schemes, direct tripping for all faults occurring in the first 80..90 % of the line section protected, independently of the communication can be achieved by using ordinary distance protection as a basic or an additional protection.

11.7 Deblocking overreach protection systems

This protection system is a combination of both permissive and blocking overreach protection systems described in sections 11.5 and 11.6 above. The zone A in a switched scheme or zone 2 in a full scheme is set overreaching and during normal operation continuous "guard" signals are transmitted. Thus, there is no necessity to use separate fault detectors or starting elements as needed at the blocking overreach system. Zone A in a switched scheme can be a separate measuring unit in the same as at permissive overreach system.

In the case of an internal fault a "deblocking" signal, is sent to the opposite end by zone A of the switched distance protection or zone 2 in a full scheme. This received telecommand will deblock the overreaching zone and tripping will occur.

If at the same time as the continuous guard signal disappears and no "deblocking" signal is received at the near end, then during a certain time period (100-200 ms) the overreaching zone is deblocked (without receiving signal) and this zone is able to trip the circuit breaker. Hence, the loss of a command "to deblock" does not necessarily result in a failure to trip as in the case of permissive overreach schemes described in section 11.5.

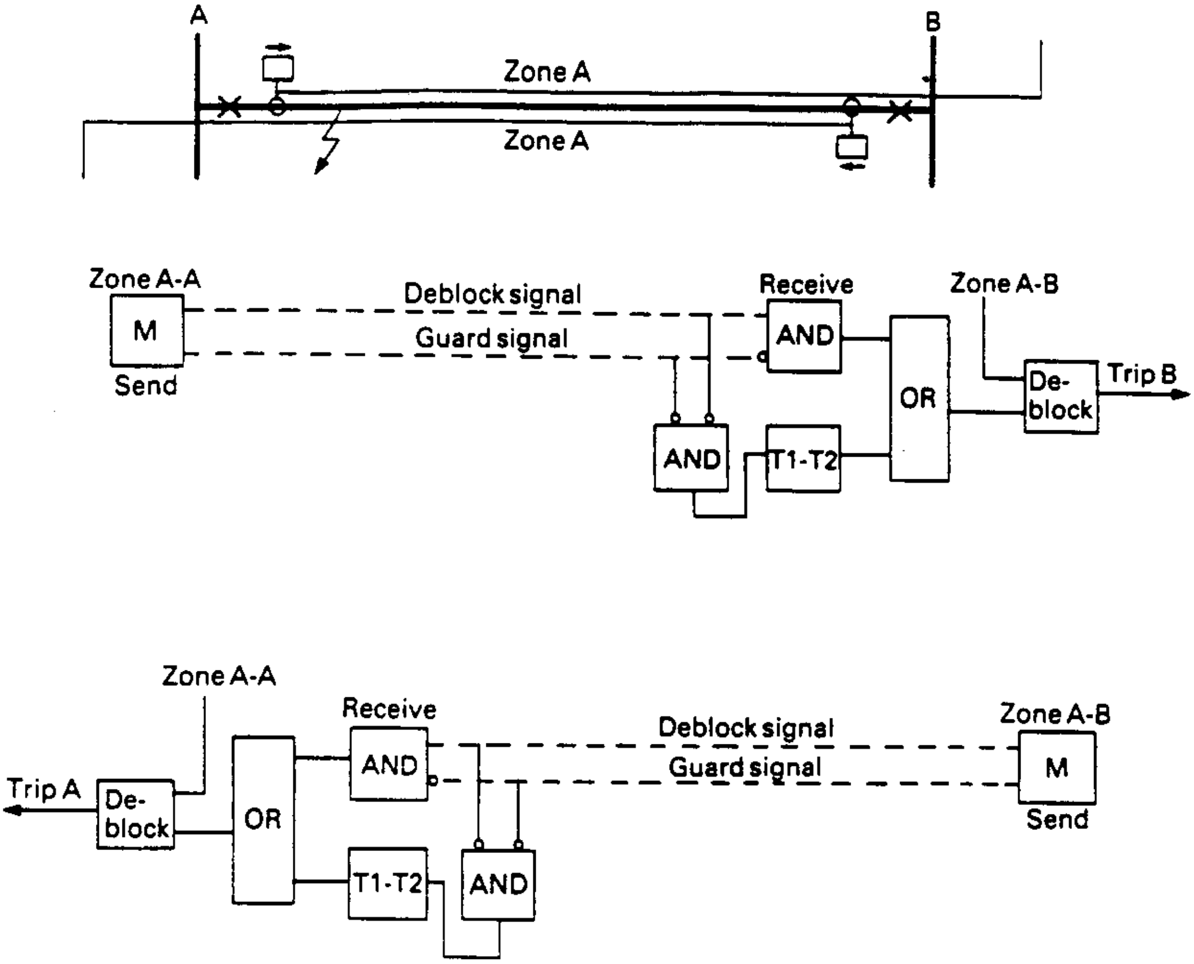
This scheme operates thus as a permissive overreach scheme during normal operation of teleprotection, but in case of channel failure it acts as a blocking scheme for a short duration. - The window period -.

The use of overreaching settings of zone A can be advantageous when applying this system to relatively short transmission lines. Fig 11:9 shows a typical scheme of deblocking overreach protection system.

As in the case of permissive overreach and blocking overreach distance protection systems, it is also possible to use "deblocking schemes" together with "accelerated distance protection systems". The window scheme can be applied to almost all distance protection system using telecommunication.

In view of the fact that a continuous guard (blocking) signal is always being sent even if there is no fault on the system, it is easy to implement the channel monitoring circuits without increasing the complexity. The loss of a channel, once detected, can be used to switch back the distance protection relays to the conventional mode of underreach operation.

The requirements imposed consequently on the signal channel, will also be less severe than in the permissive overreaching modes. Unwanted tripping can occur only if a channel fails within 100-200 ms after a fault at positions external to the line protected but within reach of zone A elements.



- Zone A is normally blocked. A received deblocking signal when the guard signal has disappeared will deblock Zone A and trip the circuit breaker.

- Guard signal is sent continuously during normal operation. If no deblocking signal is received after the guard signal has disappeared Zone A is deblocked during a period T1-T2 (window). T1-T2 is normally set on 100-200 ms. Similar window-arrangement can be applied to other schemes.

Fig 11:9 Deblocking overreach distance protection system.

Separate channels are required between each terminal. With a narrow band frequency shift carrier, significant channel spectrum is not required on 2-terminal lines. In the case of a terminal with an open circuit breaker or in the case of a weak infeed, etc. special arrangements have to be made to make the deblocking scheme function correctly.

Within their respective ranges of application all forms of communication link may be used, provided they satisfy the requirements for speed and reliability as well as the condition that under normal operation, even without any fault anywhere in the system, a continuous signal transmission is required.

11.8 Direction comparison protection systems

Basically this type of protection system is very similar to permissive or blocking overreach distance protection systems with the difference that instead of distance protection, either directional power or directional overcurrent relays are used at each end. If the directional relays are required to be very sensitive, very often an additional overcurrent or underimpedance relay is added as a permissive criterion.

The directional relays which detect phase faults are polarized by the voltages at the relaying point. The earth-fault directional relays may be polarized by either a zero sequence voltage or some reference current, as for example the current in the neutral earthing connection of a convenient power transformer local to the relay position. The transmission of the blocking command is initiated by the non-directional relays and interrupted by the directional relays.

The operating values of the phase-fault overcurrent starting relays will be restricted by the maximum load rating of the protected circuit, and this may cause problems in difficult cases where the minimum short circuit currents are comparable with the maximum load currents. The high sensitivity possible with the earth-fault protection of the direction comparison type makes it a useful supplementary feature of some distance protection schemes which may considerably limit the value of earth-fault current where it is necessary to detect earth-fault resistances or unsymmetrical situations. Fig 11:10.

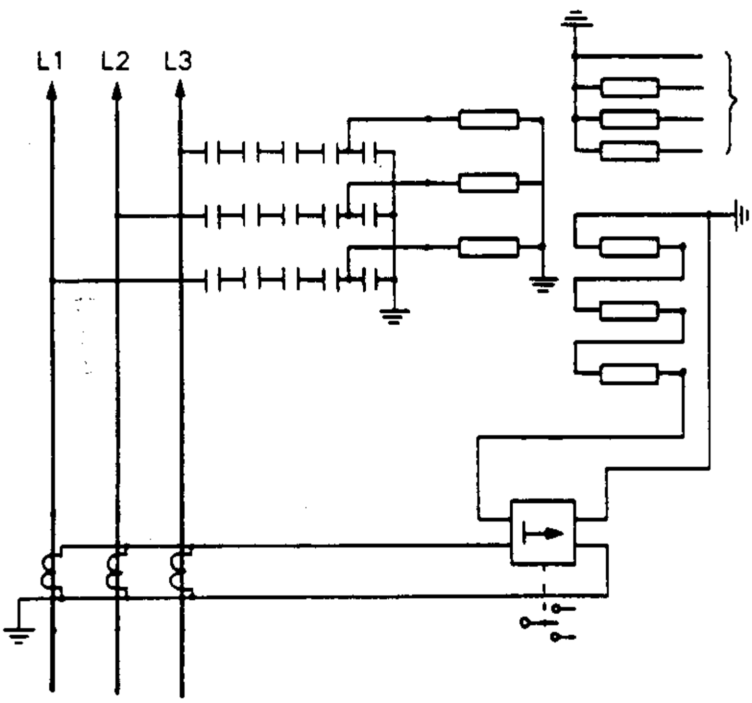


Fig 11:10 Sensitive direction protection for high resistance faults.

Similarly, schemes using a permissive overreach protection system described under section 11.5 can also be applied together with the directional relays.

All forms of communication links may be used within the limits of their range of application. High reliability and fast overal transmission characteristics are required for the reasons mentioned in sections 11.5, 11:6 and 11.7 above, depending upon application mode (permissive or blocking or deblocking).

If fast direction protection (2-8 ms) (transient protection) is applied it may also be necessary to consider the use of appropriate equally fast teleprotection.

11.9 Intertripping

As mentioned in chapter 6, there are various conditions on the power system which neccesitate tripping a circuit-breaker remote from the protection position. This requirement is frequently met when transformers and reactors are connected to the power system without circuit breakers. The power line and e.g. the transformer must be protected together, and certain problems arise from this requirement. It may not be possible to provide adequate protection of the transformer by power line protection located at the far end of the line, because:

- A fault in the transformer tank may be detected by Buchholz (gas/oil relay) with only negligible fault current.

- The fault current for a transformer fault may be limited in value. For example, in case of an earth fault on the delta winding, a relatively low value of fault current would result in the line because of the impedance of the transformer winding; the same is valid for an earth fault in star-winding near the neutral. Blocking signal against energizing of the transformer must be sent to the remote end in case of transformer fault.

- It may be necessary to distinguish between line reactor faults and line faults, especially where reclosing for the faults on the transmission line is applied. In case of reactor faults it would then be necessary not only to trip at the remote end but also to block a subsequent reclosure.

Another particular condition is where two relatively heavily interconnected power systems, each basically self contained, are interconnected by a synchronous tie, which may not be effective when one of the systems is heavily disturbed by a fault. One example of this is an interconnection between two different countries for purposes such as interchange of surplus power. The occurrence of a fault on one system may not produce tripping conditions at the relays on the interconnecting tie, which should be tripped in order to limit the effects of possible subsequent power system swings. As the fault position may be considerably distant from the interconnection, a tripping command may have to be transmitted over a relatively large distance (300-500 km) possibly over or through a number of intermediate stations.

When generating stations are separated from the switching stations (e.g. some hydro-electric schemes, where a number of individual points may be grouped at a common switching station or a thermal generating station separated from its switching station to reduce the pollution of the insulators at the switching station, and distances involved are of the order of 1 to 20 km), teleprotection between the generating and switching stations is then required both for protection and for tripping commands.

Nowadays it is common to let busbar protection and circuit breaker failure trip circuits breaker in adjacent stations by means of intertripping schemes. They are described in more detail in chapters 6 and 7, figs 6:9, 6:10, 7:5.

In view of the fact that the telecommand at the receiving end can by itself initiate switching without any local permissive criterion, the same stringent requirements as described under 11.3 are applicable here as well. However, in many of these cases, where PLC is used, the signal is sent over healthy power lines.

Operating mode	Under-reaching sending	Over-reaching sending	Permissive criteria receiving
Permissive underreach	Zone 1		under imp. under volt. over curr. distance direction
Intertripping underreach	Zone 1		None (coded signal)
Acceleration underreach	Zone 1		Zone A or Zone 2
Permissive overreach		Zone A or Zone 2	Distance and direction
Blocking overreach		Reverse looking (starter)	Distance and direction
Deblocking overreach		Zone A or Zone 2	Distance and direction

Zone A in switched schemes
Zone 2 in full schemes

Table 11:1 Protection systems using telecommunication.

12 TELEPROTECTION SYSTEMS

12.1 General

As shown in clause 9.1 we can subdivide a protection system using telecommunication into three different systems:

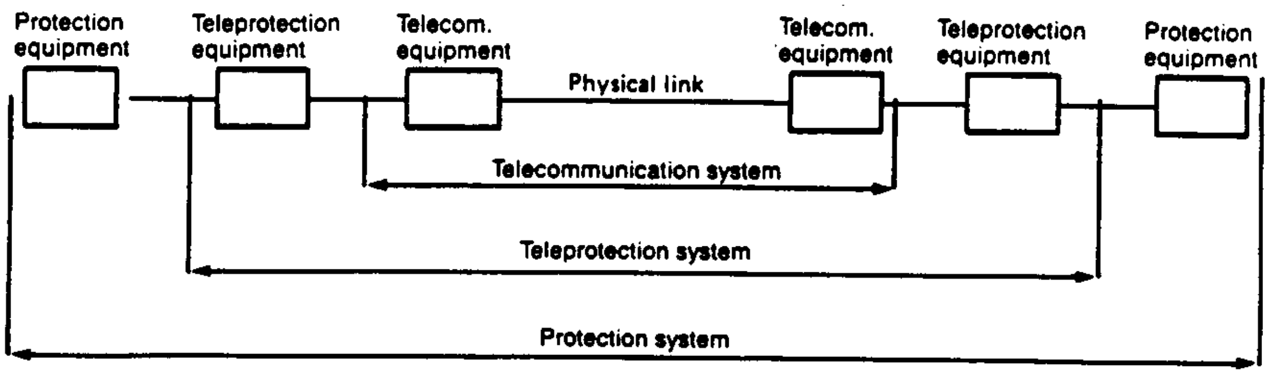


Fig 12:1 Diagram for protection systems using telecommunication

The inner system is the telecommunication one which is composed of the physical link and the telecommunication equipment (see also clause 13).

Then there is the teleprotection system composed of the teleprotection equipment and of the telecommunication system.

The whole embracing system is the protection system using telecommunication.

The task of the teleprotection system is to convey a protection signal to the other end in a proper way.

When using cable systems it is possible to transmit signals coming from the protection equipment in the same way as they are produced. More developed cable systems and all other telecommunication systems use modulation processes to adapt incoming signals to the transmission band of the communication link.

At the receiving side a demodulation process takes place to form a similar signal as that delivered from the protection equipment at the sending side.

With the exclusion of some particular cases of telecommunication equipment specially built for the transmission of protection signals (as for instance PLC equipment directly modulated in the HF band), the telecommunication equipment used is that employed in normal telecommunication systems. Therefore teleprotection equipment is used with the task of modulating (and demodulating) signals coming from the protection equipment and to transform them in a way compatible with the modulation band which is peculiar to the telecommunication equipment.

According to the number and type of signals to be transmitted, the type of transmission adopted and especially the requested response time, the transmission bandwidth is variable from some hundreds of Hz to some tens of kHz.

Teleprotection systems show characteristics and performances which differ considerably if they are based on the transmission of command signals or of measured values.

The principal parameters of interest are linked to the possibility of correct transmission of information within an environment impaired by noise (e.g. noise arising from sources external to the equipment). Let us take into consideration separately the aspects and consequences of the two aforesaid cases.

A

Considering a command system, the information to be transmitted is represented by the change of state OFF-ON or vice versa of certain signals. The telecommunication system has to guarantee the correct reception of this change of state within a specified time.

The bandwidth needed for transmission is determined by the required transmission time and is linked to the response of the communication link to a step input. The wider the band, the faster will be the response.

Naturally, as the system works in an environment influenced by noise, the theoretical assumptions made are not perfectly true owing to some drawbacks which appear. If, to have a fast response, the transmission bandwidth is widened, then the noise captured by the receiver is increased and this increase in noise risks destroying the information decoded. To be able to decode this signal, it is therefore necessary to proceed to an integration of the output signal from the decoder (or demodulator) and this process is time consuming: the time gained with band widening is therefore spent in decoding, so that it is necessary to reach the optimum compromise.

The integration of the signal may be carried on traditionally or may be based on correlation processes or also may be achieved by adopting the method of transmission of a digitally coded signal and hence on its acknowledgement.

By modifying the duration of the integration time, one obtains completely different results. Too long an integration time may produce a good output signal but with a delay greater than the maximum permitted value, i.e. no signal received, while too short an integration time risks producing an output from the decoder due to the noise, which means an unwanted command.

These two aspects, just described, are the two sides of the same characteristic which is called reliability. The first aspect is linked with security, while the second is linked with dependability (See also clause 12.2).

B

In dealing with analogue systems we speak of teleprotection systems where the information to be transferred is not a change of state, as for command systems, but is represented by the measured value of a certain electrical quantity; at the receiving side the protection equipment makes a comparison of the received quantity with the corresponding local one in order to produce the command signal. The operation of the protection equipment at the receiving side is based on a comparison between the received quantity and the corresponding local one.

Also in this case, the bandwidth needed for the transmission is fixed both by the number of the measured valued transmitted and by the required transmission time.

As stated earlier the telecommunication system will be influenced by noise which will be regarded as an analogue quantity. At the output there will be a quantity reproducing the transmitted one with a certain error. If the error is greater than a specified value, there may be, as a result of the comparison in the protection equipment with the local quantity, an unwanted command or a missing command.

Also for this kind of system, taking into account an integration (which can take place on the measured quantity at the output of the teleprotection receiver or at the output of the comparison circuit of the protection equipment), an increase of the security can be achieved (greater probability of not receiving an unwanted command) but the dependability is worsened (less probability of not having a missing command) (See also clause 12.2).

From the point of view of the protection system as a whole, the concept of reliability with its twin faces of security and dependability continues to be valid, but if the consideration is limited to the teleprotection system alone, such a concept loses its significance and its importance.

The characteristics, which have to be considered for the teleprotection system, are response time and deviation or errors introduced in the reproduction of the transmitted quantities.

For analogue teleprotection systems the transmission of information can be realized in different ways.

With a telecommunication system by cable at ones disposal the analogue signals can be transmitted as they are given by the protection with no modification. This system however is subject to the limitations, also valid for the transmission of command signals, caused both by the physical parameters of the cable (stray capacitance and series resistance) which produce attenuation and distortion of the transmitted signals, and by problems tied with insulation and protection of circuits against induced overvoltages from switching and lightning.

To overcome these limitations, use is made of various kinds of modulation processes.

With an analogue modulation system, the signal to be transmitted in a continuously modulates manner a carrier frequency, one or more characteristic quantities of which (amplitude, phase, frequency) are proportionally modified. Another way of implementing an analogue system is by transforming the analogue signal into a digital quantities signal made by a sequence of logical "ones" and "zeros" by means of an appropriate analogue-to-digital coder; the digital signal produced in this way is applied to an ordinary modulating apparatus similar to a modem for data transmission.

This brief exposition of considerations can be summarized in the following.

The characteristics, which are of interest for a communication system used for analogue protection systems, are:

1. The response time in a non steady state to an input step signal

2. The degree of noise immunity

3. The linearity in amplitude and phase, if more than one signal is to be transmitted.

This means the ability to reproduce, with constant error or with errors limited within specified bounds, signals with different characteristics appearing on the transmitting side.

12.2 Availability and Reliability

As for the protection system, reliability is of utmost importance in the teleprotection and telecommunication field. To make a system more reliable it may be necessary to introduce redundancy which will also increase the availability.

Different levels of redundancy can be implemented.

For the telecommunication systems it is necessary to take precautions against possible interruptions of the communication link caused by faults on the equipment.

Two different designs can be implemented using duplicate systems.

When one of the two systems is normally switched off, the so called "cold standby" is obtained. Here the main object is to increase availability. In the case of a fault on the main telecommunication system, normal operation can be re-established by switching and commuting to the spare system.

When the two systems are both in operation, the so called "hot standby" is obtained. In this case the service is obtained without appreciable interruption by automatic switching from the faulty to the healthy system in case of a fault on the main system. Here both availability and dependability are improved.

The dependability of the whole system can be further improved by incorporating redundancy into the links as well as in the equipment. This can be best achieved by using two different routes for the links, or utilizing two links based on different physical principles.

One PLC link and one radio link are often used as reserve links for each other. When using only radio links, either space diversity (using different physical paths) or frequency diversity (using two different frequencies for the two links) will fulfil the requirements.

All systems will usually have some common parts, e.g. station batteries or mains power supply. If further redundancy has to be implemented, these parts should be duplicated or given better security by other forms of redundancy.

Increasing the redundancy of a piece of equipment may be done by increasing or duplicating important and critical parts. Examples of this are modular power supplies, carrier frequency generators and transmitter power amplifiers.

Within one amplifier for example additional transistors in parallel will increase the redundancy if the amplifier can work when one or more transistors are faulty. An alarm should always be given to indicate when part of the equipment is faulty even though the equipment may be working satisfactorily.

In the field of equipment and components however, there may be found also partial redundancy of the type 1/n. For example this is the case when the principal function or job can be maintained by n-1 equivalent apparatus working in parallel, in the case of a fault of one of them. Applications which show this rule may be found in the field of equipment power supplies (more power supplies in parallel, one of which is redundant) or of power amplifiers in radio transmitters.

It is worth noting, at least, that operating some apparatus in parallel may have a different meaning from redundancy if the objective is to achieve increasing security of the system at the expense of reduced availability. In this case the system may be implemented with two or more apparatus units working in parallel, but the behaviour of the system may be considered valid for instance only if all apparatus present a similar indication.

A fault on one or more apparatus units generally inhibits the operation of the system and in this case consequently no redundancy at all exists for the system itself. In dealing with the specific field of protection systems, a typical way of implementing this concept is with command teleprotection equipment adopting double frequency shift keying. The transmission of the command signal is considered successful only if the two transmitted frequencies are shifted; if this is not the case the output of the receiver is kept blocked.

In addition to the reliability aspects mentioned above, which are applicable in general to all equipment, the overall performance of teleprotection systems is also affected by noise arising from sources external to the equipment (e.g. noise due to power line faults, lightning, isolator and circuit breaker operation etc).

The specific aspects of dependability and security of teleprotection systems due to noise (briefly mentioned in clause 12.1) are explained below.

Dependability

Dependability of a teleprotection channel is given as the percentage of commands sent reaching the receiver within a time stipulated as the maximum transmission time.

Instead of dependability, it is often more convenient to use the expression "Probability of missing command P_{MC}". If we are sending N_T commands and N_R commands are received within the given time then:

$$P_{MC} = \frac{N_T - N_R}{N_T} = 1 - \frac{N_R}{N_T}$$

$$\text{Dependability} = 1 - P_{MC}$$

Fig. 12.2 shows an example of measured curves for the dependability of a single teleprotection channel . The curves are given for P_{MC} versus the S/N-ratios for various transmission times T_{ac}.

Security

Security can also be expressed as a function of the "Probability of unwanted commands P_{UC}".

This can be given as a number of unwanted commands for a period of one year.

Common to all types of telecommunications channels used is that the noise under normal working conditions is so low that unwanted commands are not likely to occur.

Only high noise level will influence a teleprotection receiver. Such noise will mostly be impulsive noise generated by lightning, by operation of isolators and circuit breakers, induced noise into cables or switching noise from exchanges. For radio-links fading may decrease the signal-to-noise ratio S/N to unacceptably low values. (See also chapter 13).

Most of this noise will only last for a short time, ranging from some milliseconds up to some seconds. The duration probability of this high noise over a long period will also be very short, typical $P_N = 10^{-4}$ to 10^{-6} of the time.

To get a figure for security or for the probability of unwanted commands, the teleprotection channel can be tested by inserting bursts of high level noise at the receiver input at the same time as a guard signal is transmitted.

The number of unwanted commands N_{UC} to the number of noise burst N_B sent will then give a measure of the probability of unwanted commands (see figure 12.3).

$$P_{UC} = \frac{NUC}{N_B}$$

$$\text{Security} = 1 - P_{UC}$$

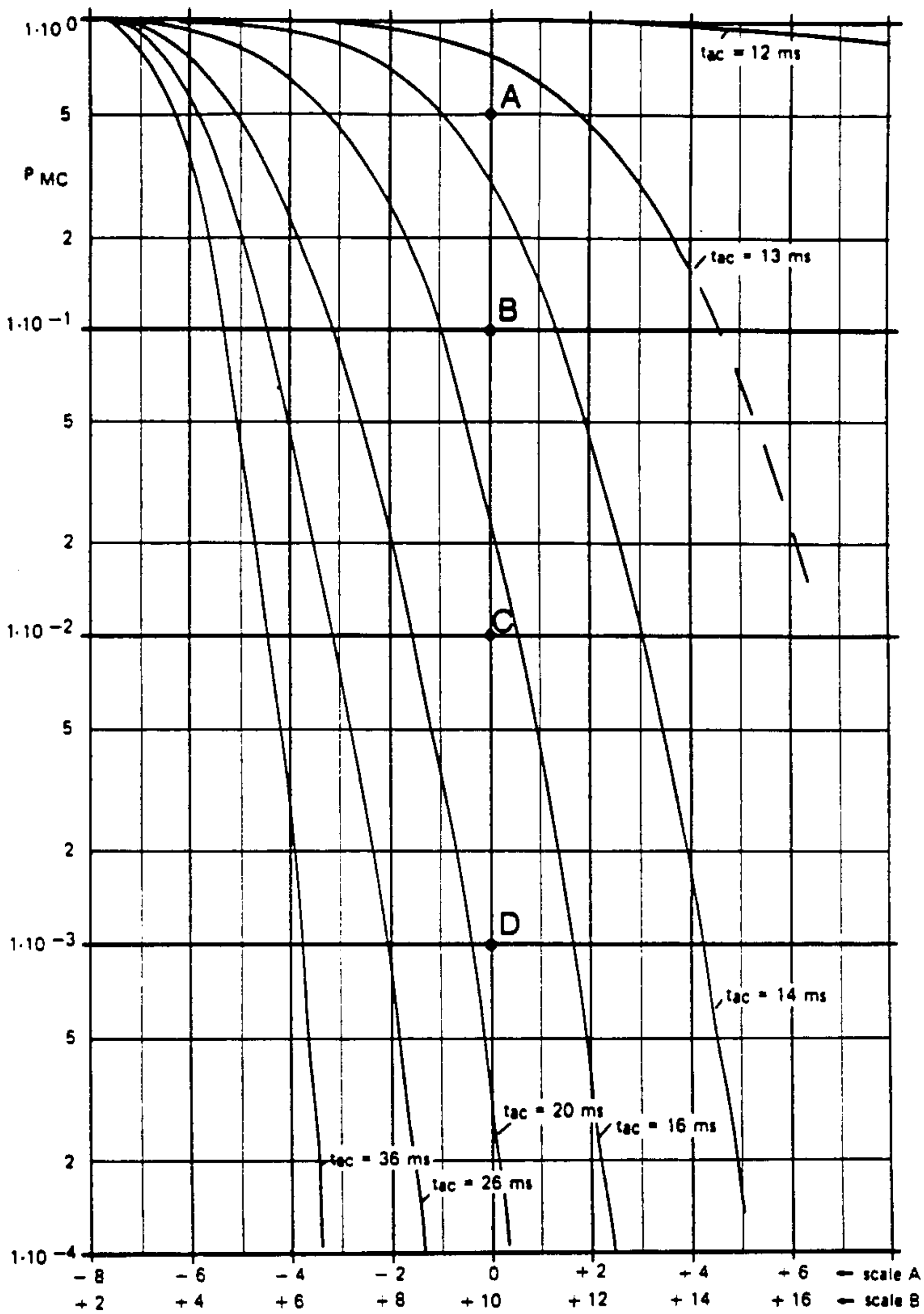
When combining the probability of unwanted commands P_{UC} with the probability of the high noise P_N, it may be possible to have a figure of the probability of unwanted commands in a year P_{UC} (year) if a noise model of P_N can be given (see appendix).

Availability

The availability of equipment is also very important. This will depend on the MTBF (mean time between failure) and the MTTR, e.g. time it takes to repair a fault (MTTR mean time to repair).

Availability is given, as is well known, by the formula:

$$A = \frac{MTBF}{MTBF + MTTR}$$



S/N - ratio in dB

scale A: Noise bandwidth 4000 Hz (Baseband)
scale B: Noise bandwidth 400 Hz (Channel band)

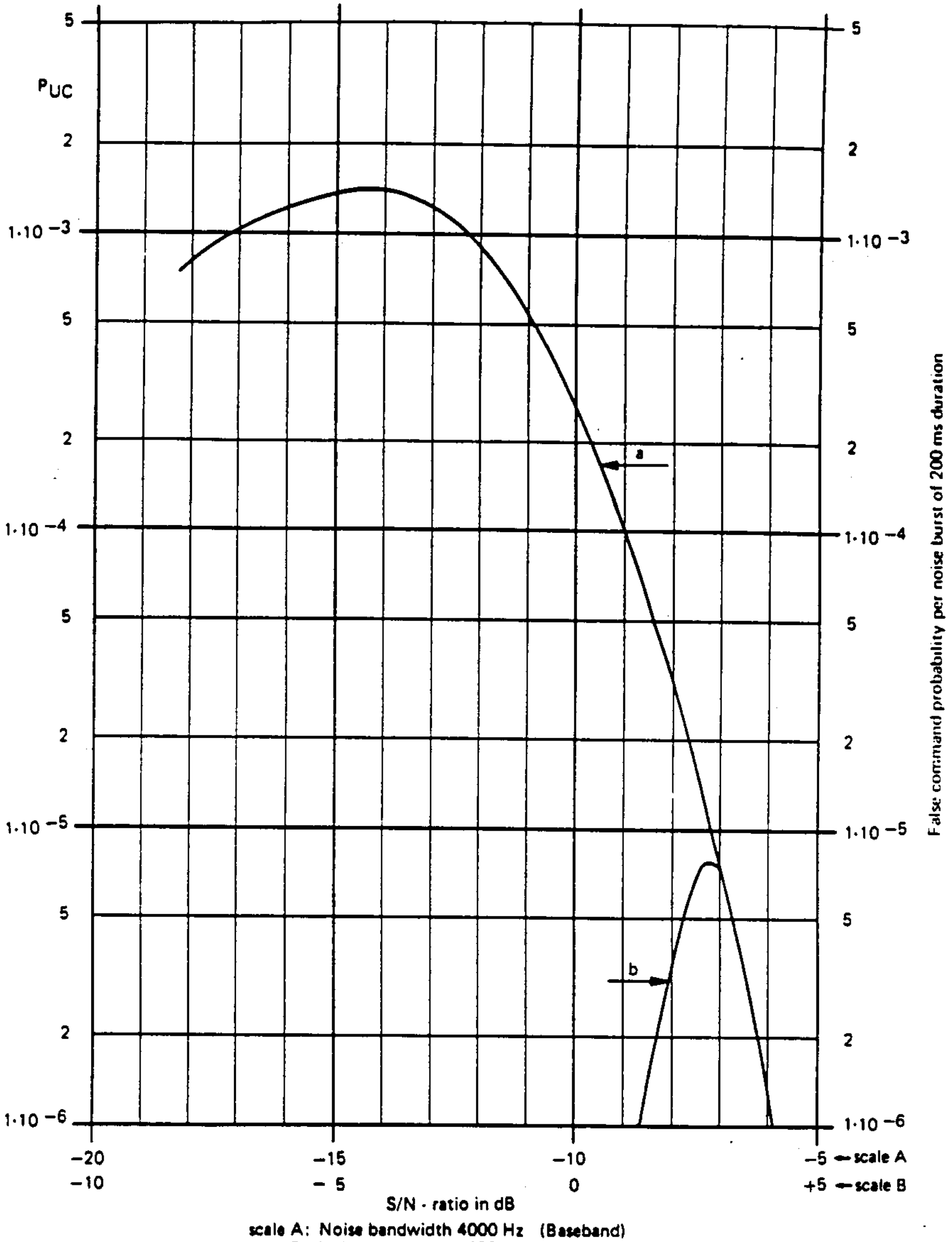
Actual transmission time tac as parameter

As an example it can be seen that 50% of all commands are using approx. 13,5 ms at a S/N = 0 dB where noise is measured in a 4 kHz bandwidth (A). For higher dependability, the transmission time will increase to

	approx. 15 ms for 90%	P_{MC} = 10-1 (B)
	approx. 17 ms for 99%	P_{MC} = 10-2 (C)
and	approx. 19 ms for 99,9%	P_{MC} = 10-3 (D)

Probability of missing command versus S/N for a 200 baud channel

Figure 12.2



scale A: Noise bandwidth 4000 Hz (Baseband)
scale B: Noise bandwidth 400 Hz (Channel band)

Curve a: Without noise blocking device.
Curve b: With noise blocking device.

Probability of unwanted commands versus S/N for 200 baud channel

Figure 12.3

12.3 Analogue systems

Fundamental to analogue teleprotection systems is the transmission of electrical parameters such as primary current (phase or amplitude) between both ends of a protected line, and their comparison with the local parameters.

As with be readily understood, this comparison must be made between magnitudes at the same instant. This implies that the transmission and comparison system must be as fast as possible.

The speed of the transmission and decision circuits will adversely affect the security and dependability of the whole protection system.

One may differentiate between two teleprotection categories based on the information transmitted;

- the non segregated, in which the three phase current values are converted into a single phase current by a composite sequence network,
- and the segregated, which converts and transmits individually the parameters of the three phases in the protected circuit. This gives a particular advantage in single phase reclosing.

The current value from the non segregated system can be transmitted within one audio channel for each direction, while the segregated system needs several audio bands or a group band for each direction.

In these protection systems it is difficult to define the borderline between the teleprotection system and the protection equipment itself, as opposed to the command systems.

The following is a description of those protection systems using telecommunication. We may distinguish between:

A) Longitudinal differential teleprotection

The longitudinal differential teleprotection system is based on a comparison of power frequency signals proportional to the primary power system current (amplitude and phase angle).

The transmission of the current value may be done via a pilot wire, radio link or a fibre optic link. The telecommunication equipment may be modulated in two different ways:

- **Frequency Modulation (FM):**

  A carrier signal is frequency modulated by the instantaneous value of the primary current at each line end. The maximum value of the frequency deviation is approximately 1 kHz.

- **Pulse Code Modulation (PCM):**

  The instantaneous current value at each end is sampled synchronously and the resulting digital data is transmitted to the opposite end by Pulse Code Modulation. The instantaneous current is sampled several hundred times per second, which means 12 to 160 samples per period of the primary current, and then converted into 8 or 12 bit digital data.

  The comparison is done differentially between the instantaneous current values, the local and the one from the other end. A circuit delay must be provided for the local signal to compensate for the transmission time for the remote value.

B) Phase comparison teleprotection

The phase comparison teleprotection system is based on a bidirectional transmission of the primary current phase from the two power line ends, and a comparison with the local phase angle in order to determine whether the fault is internal or external.

From the point of view of teleprotection and telecommunication requirements, we can distinguish between;

- **Half wave comparison teleprotection:**

  This teleprotection system transmits, generally when a starter relay has operated, a square wave which corresponds to the positive and negative half-cycles of the primary current.

  An "on-off" carrier is modulated by this square wave switched "on" during positive half-cycles, and "off" during negative, or vice versa.

  Some teleprotection equipment has an adjustable current threshold value in order to compensate for capacitive current. Some equipment also has an adjustable circuit delay at the input of the local signal to compensate for the remote signal's transmission time.

  The comparison function is based, as explained in 10.6, on the comparison of the phase angle between received and local signals. If this angle is greater than a predetermined value (stabilizing angle) the fault is internal, and if less the fault is external.

  This teleprotection system has a blocking scheme. For an internal fault, if the signal from the other end is not received, the output of the comparator circuit sends a trip command when the low set and high set relays are activated.

This teleprotection system might behave incorrectly in some situations due to the noise generated during a fault. For an internal fault the noise might simulate a transmission signal from the other end and might block the protection equipment, or for an external fault the noise might generate distortion at the receiving end, deblocking the protection equipment.

- **Full wave comparison teleprotection:**

  In this teleprotection system the composite phase current value is transmitted constantly between both ends of the protected line. Local and remote signals are then compared for the positive and negative half-cycles.

  Generally, an FSK signal modulates a telecommunication channel. This can be a pilot wire, power line carrier, radio link or fiber optic link.

  Unlike to the previous system, this one has an unblocking scheme. The telecommunication system continuously monitors itself and when a fault occurs, the teleprotection equipment compares the local signal with the remote, doing this for both positive and negative half-cycles. If the phase angle is greater than the stabilizing angle, the protection equipment is unblocked.

  If the signal-to-noise ratio at the receiver is too low, the teleprotection system is blocked and gives an alarm. The use of a transmission system, independent of the power line to be protected, will give the system better dependability.

  This type of teleprotection, just as the previous one, compares electric magnitudes that occur at the same instant, which means the transmission must be very rapid. In order to attain a good performance from the protection system we must have a telecommunication system with a good signal-to-noise ratio, and little telegraph distortion.

- **Segregated phase comparison:**

  As stated in 10.6, the need to know the faulted phase in a faulty power line when handling heavily loaded EHV lines and parallel circuits on the same tower, makes it necessary to transmit each of the phase values independently of the others.

  This comparison system (segregated) is similar to the other and compares the received signals from the other end with the local ones, in this case phase by phase, When the phase angle is greater than the preset stabilizing value, it permits the breaker to trip.

The transmitted signal may be digital or analogue. If an analogue transmission is used, the values of each phase are transmitted via independent channels. In the case of digital transmission, the value of each phase is transmitted in a message in series format with a control code. This signifies that, in order to compare instantaneous values, a high speed channel will be necessay, somewhere around 48 /kbs. Normally, telecommunication systems used for these teleprotection systems are radio or fiber optic links.

12.4 Command Systems

As pointed out earlier, a command teleprotection system is part of a protection system. The teleprotection signals transmitted will either be used for aiding the protection system in improving the performances, or will be an essential part of the system. In the last case, the protection system will not work in a proper way without the teleprotection signals.

In both cases it is essential that a signal transmitted from one station shall be received and reproduced as the same signal at the receiving station so that the right command can be given.

If the signal is influenced by noise, the signal received can be misinterpreted by the receiver and a false command given. In this case the teleprotection system has failed and a wrong command may be given.

To meet the requirements fased by the protection system some parameters are essential for the proper operation of the teleprotection system. They are:

- Transmission time
- Dependability
- Security
- Availability

} See chapter 12.2

Transmission Time

The protective relay, the circuit breaker and the teleprotection channel will contribute to the total fault clearance time T_C.

The maximum allowable fault clearance time is dependent upon the power network structure and the operating philosophy. When newer equipment is used this time will decrease, which will result in pressure to obtain shorter and shorter transmission time for the teleprotection channel.

The transmission time for a teleprotection channel will depend on various factors. The bandwidth is essential, but heavy noise will also increase the transmission time (see figure 12.2).

Channel bandwidth is expensive. To save bandwidth a teleprotection channel is often used together with data channels and a speech channel all sharing the same 4 kHz band. The bandwidth occupied by the teleprotection channel will be equivalent to a 100, 200 or 400 baud data channel.

Figure 12.4 gives a survey of the combinations of the various times used by the equipment involved in clearing a line fault.

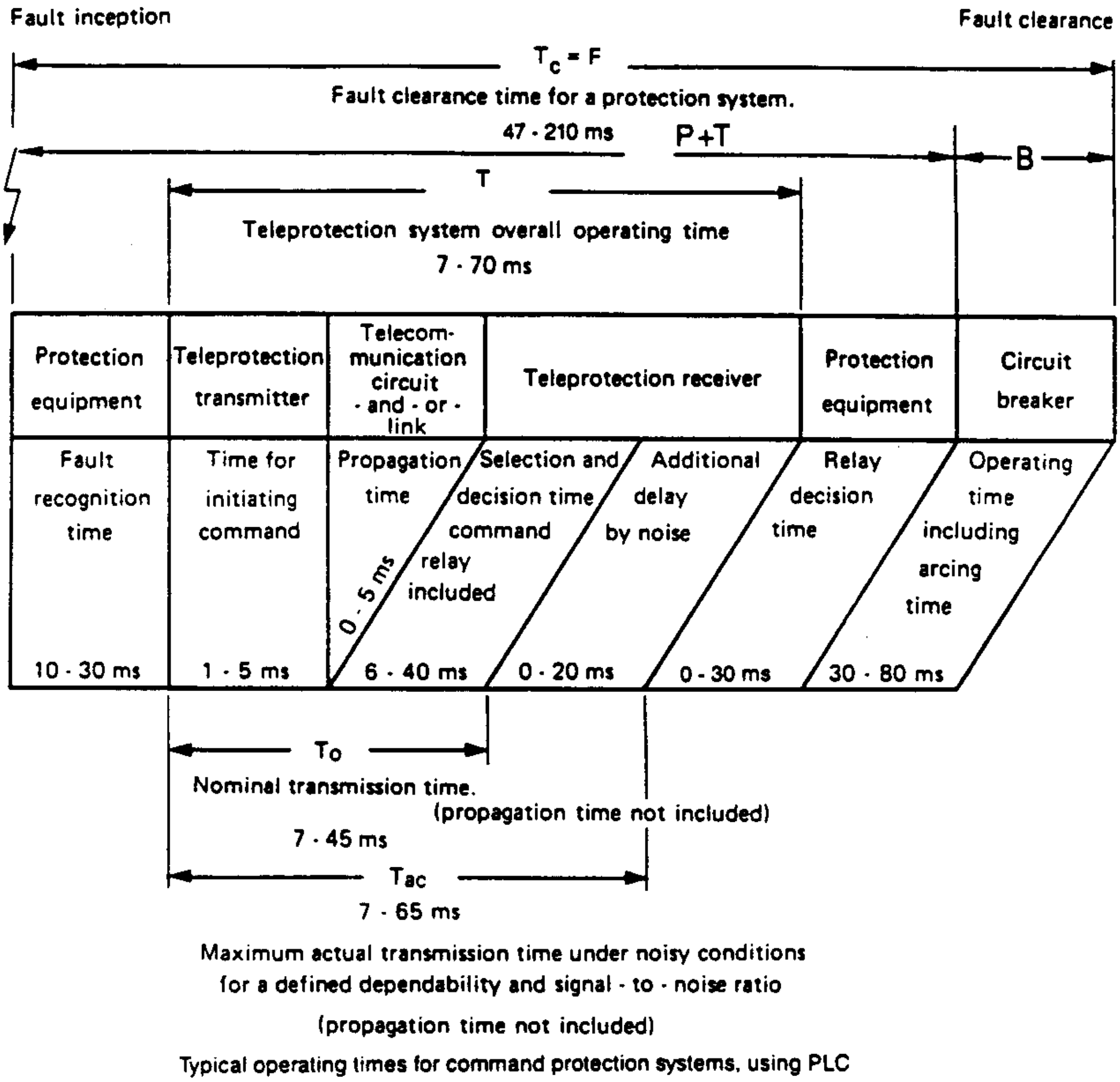


Figure 12.4

For 100 to 400 baud channels a minimum transmission time of about 8-10 ms can be achieved. If more speedy channels are needed, a broader bandwidth as a whole 4 kHz band or even a multiple of 4 kHz bands have to be used.

This can be done if enough bandwidth is available and the cost is acceptable.

Alarm

The telecommunication equipment and the teleprotection equipment will give an alarm if the equipment is not functioning in a proper way. When an alarm is initiated, the teleprotection receiver is blocked, preventing a command output.

The alarm has moreover the task of informing the maintenance party in order to keep the "Mean time to repair" (MTTR) as low as possible.

Teleprotection equipment requirements

The transmitter will receive the guard/command information from the protection equipment as a DC signal. This signal has to be transferred into a signal suitable for transmitting as a voice-frequency signal within the 4 kHz band used.

Normally the sender will transmit the guard signal as an upper frequency signal (bit information = 0) within a frequency shift channel at a rate of 50 to 600 baud. When a command comes, it is transmitted by changing the state of the transmitter (see figure 12.5a). This is done in different ways.

By coded command signals the transmitter will send a range of bits by shifting for example from upper frequency (0) to low frequency (1) in a certain way. This bit range has to be acknowledged by the receiver before a command is given (see figure 12.5b).

A command signal can also be sent only by shifting the frequency from upper frequency (0) to low frequency (1). In this case (0) means the guard state and (1) means the command state. A processing operation has to be done at the receiver to check if the (1) is a real command and not only noise, before a command output is given (see figure 12.5b).

Sometimes two FSK-channels are used together. In this case the two channels are changing the frequencies in opposite ways, when changing the state. The upper frequency in the first channel and the lower frequency in the second channel give the guard state. The command state is given by changing the frequencies in both channels (see figure 12.5c).

Normally only one FSK-channel is used, but sometimes an on-off channel is used to improve security. This can be the pilot or the signalling channel for a PLC-link. The above mentioned low frequency channel can either be transmitted directly on a cable link or modulated on the carrier circuits mentioned earlier.

Special equipment is sometimes used for PLC where the guard and command state are given by two high frequencies (within 30 to 500 kHz) with a separation of 500 Hz to 1000 Hz. This equipment will occupy appr. 1 to 2 kHz bandwidth.

The receiver shall receive and detect the signals sent from the transmitter and, after a processing operation, decide whether the signal gives a guard or a command state. In this latter case the receiver shall issue a command to the protection equipment.

The task of the receiver is very complicated. The transmission time from the moment the transmitter gets a command information, till the receiver can give out a command, must be as short as possible. This means that we need fast filters and detectors, which at the same time must have the necessary selectivity. Processing the signals through noise is also a difficult problem. At the same time this processing and decision time shall be short and must not influence the necessary security and dependability.

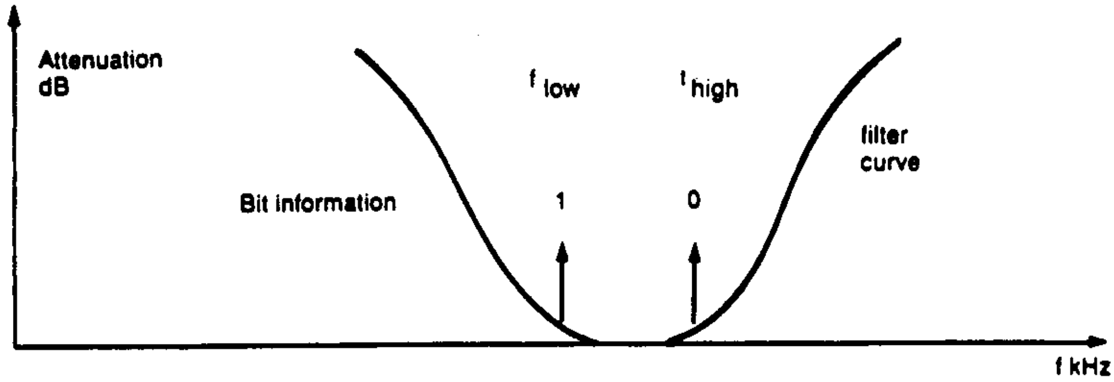


Fig 12.5a Frequency shift channel

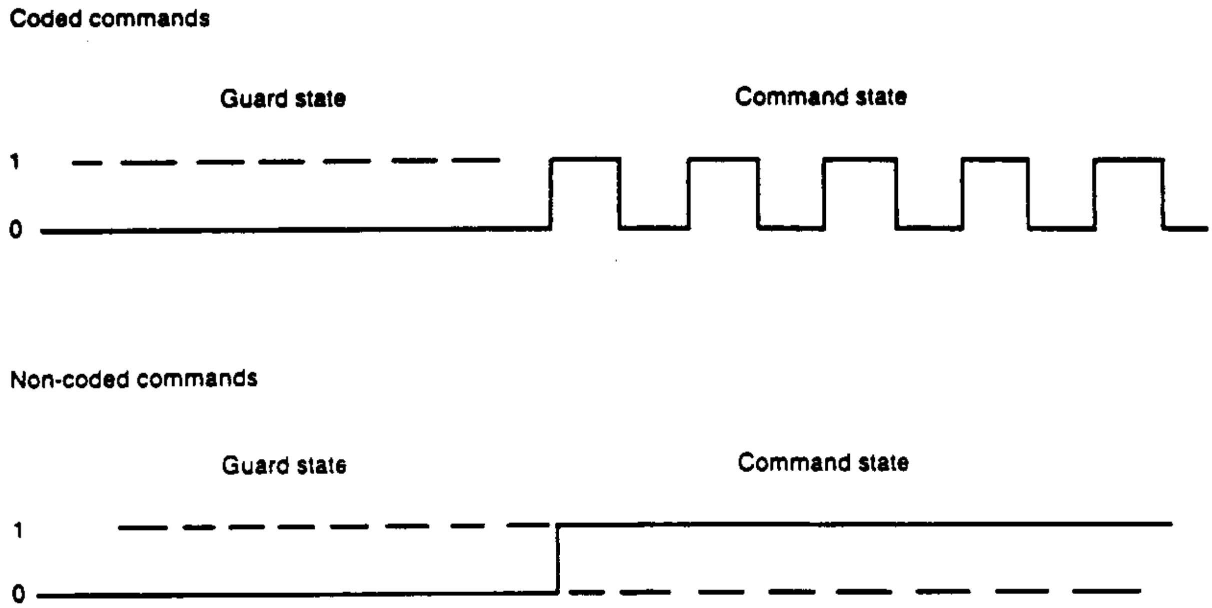


Fig 12.5b Guard/command states

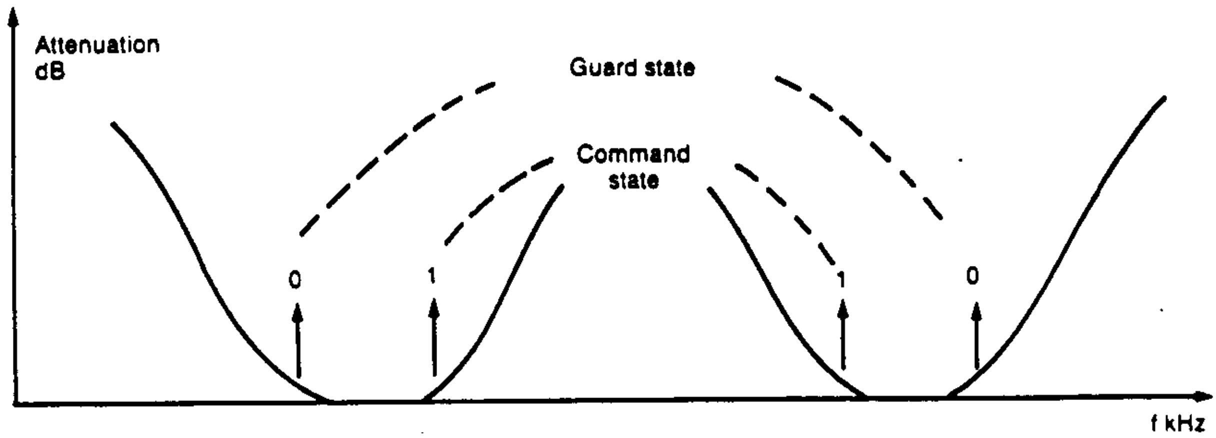


Fig 12.5c Double frequency shift channel

Noise, and in this case the heavy impulsive noise, as stated previously, will influence the receiver.

With the aid of advanced mathematical and technical procedures it is possible to recognize the guard and command signals even through fairly high noise levels. This may, however, delay a command signal.

If the noise is too strong, the receiver will often be blocked for the time the noise is above a preset level prohibiting the possibility of a false command. This procedure may delay a genuine command, e.g. at the starting time of a power line fault, but often this delay will not be significant.

Transmission time

The transmission time T or T_{AC} (see figure 12.4) will depend on the noise level. In the case of a $P_{MC} = 10^{-2}$ to 10^{-3} positive S/N-ratios from +10 DB to 0 dB (noise bandwidth 4 kHz) will increase the transmission time T_{AC} by 1.5 to 2.0 times To, while for negative S/N-ratios the increase will be greater, T_{AC} = up to 3 x T_O. Both the S/N-ratio and P_{MC} have to be taken into account when a max. allowable transmission time is given.

For different protection schemes the transmission time varies from 3 to 60 ms. If a time shorter than 7 ms is needed, broader bandwidth and higher signal level have to be used. Within a 4 kHz bandwidth as used by PLC or radio-links, a time T_O = 5 ms seems to be a limit when the whole 4 kHz band is used only for one teleprotection channel.

Precise values for different schemes are therefore impossible to give. As guidelines a range of values can be shown. Most schemes will use values within these range of values.

	T_{ac} ms	P_{MC} at S/N = 0dB	P_{UC}
Blocking command	3 to 25	10^{-3} to 10^{-4}	One unwanted command in 1 to 10 equipment years
Tripping command	8 to 40	10^{-2} to 10^{-3}	One unwanted command in 100 equipment years
Intertripping command	30 to 60	10^{-3} to 10^{-4}	One unwanted command in 500 equipment years

Table 12.1. Guidelines for important parameters for command systems

13 TELECOMMUNICATION SYSTEMS

13.1 General

13.1.1 Object

The purpose of using telecommunications in conjunction with protection systems is to convey a signal from the protection equipment at one station to a similar equipment at the remote station. Various transmission media are used:

- Pilot wires (aerial or buried systems)
- Power line carrier (PLC) systems
- Radio links
- Fibre optic links

The protection signal should be transmitted as fast as necessary to the remote station, with the highest possible dependability and security (against false signals) and with a high degree of availability.

These requirements (speed, dependability, security and availability) may vary for various protection schemes and line configurations. Practical and economical reasons may define which type of telecommunication system or systems have to be used in the different cases.

13.1.2 Baseband

All telecommunication systems have a certain band of signals which are transmitted. This band called "baseband" can vary considerably from system to system.

The performances required vary depending on the quantity of information in the teleprotection signal and on the required time for the transmission. According to Shannon's law in fact, the quantity of information transmitted by a channel is directly proportional to the bandwidth of the channel itself. For a fixed bandwidth the communication channel will be able to transmit a fixed amount of information per unit time related to the power of the telecommunication signal and to the noise of the medium. If, as in the case of protection operation, the information to be transmitted is limited, we can transmit this information in a very short time provided the capacity of the channel is sufficient or in a certain time with a certain delay if the capacity of the channel is not sufficient.

For teleprotection purposes widening the bandwidth will reduce the transmission time, but a wider bandwidth will also increase the noise power. The signal-to-noise ratio within the channel is therefore important when considering the optimum performances.

In a pilot wire the attenuation and the bandwidth are functions of the cable type, cable length and frequency. A band from appr. 0 to 4 kHz is normal. When transformers are used the lower frequency range including DC signals is blocked.

A PLC system has normally only one channel, sometimes two or four. These channels will normally have a channel spacing of 4 kHz with the useful section ranging from 0.3 kHz to 3.4 kHz or more.

This band is often shared by speech, data channels and channels used for protection purposes.

In this case in order to have successful transmission it is very important to make sure that the S/N-ratios both for the speech channel, the data channels and the teleprotection channels are sufficient, even during adverse weather conditions.

The lowest acceptable values for S/N-ratios are:

For the speech channel $S/N \geq 25$ dB
For a data channel $S/N \geq 15$ dB
For a command teleprotection channel S/N = 10 to 15 dB
For an analogue teleprotection channel S/N=15 to 20 dB

The indicated S/N-ratios are referred to the actual channel bandwidth for each channel. (See also CIGRE: Guide on power Line carrier 1979).

The minimum figures given above apply to the overall system for links connected in cascade. This means that the individual links must have a higher S/N-ratio.

Both radio links and fibre optic links have much broader bandwidth available. Here a baseband of $n \cdot 4$ kHz is used. With such broad bandwidth a teleprotection channel may have very short transmission time.

From the operation point of view, the telecommunication links are mostly realized in a "4-wire" mode. That means that the two directions of transmission are separated, allowing for simultaneous transmission of signals both ways.

13.2 Pilot wires

This was historically the first medium used for transmitting protection information between two stations. It is still in use, but normally only for short distances and where it is economical to use.

The pilot wire consists of a pair of wires used either as an overhead line or a cable, which can be hung on poles or laid underground. The pilot wire can be privately owned or rented from PTT or other companies.

The pilot wire is used mostly to transmit analogue signals like currents for differential current protection and phase values for comparison between the two stations at the end of a power line.

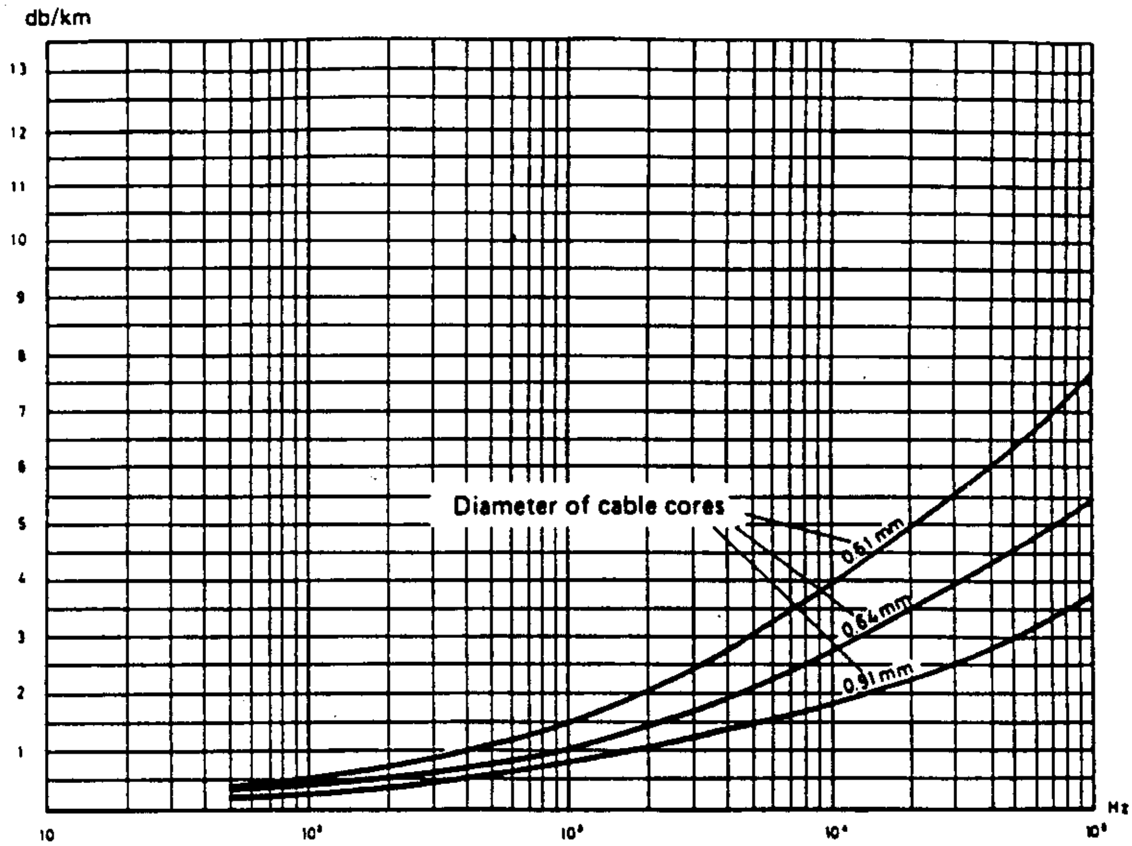
The signals are normally transmitted as power frequency values, but sometimes they are transferred to DC-signals or modulated on an audio frequency carrier in the range of 1 to 2 kHz.

The pilot wire does not necessarily follow the same route as the power line it is connected to. Rented lines, often use different routes, whereas privately owned ones may often follow the same route as the power line.

The electrical parameters of a pilot wire depend on its mechanical parameters, such as core size, insulation of the cores and their construction (twisted pairs, shielding etc) and also on the transmission frequency, as it is shown in Figure 13.1 and 13.2.

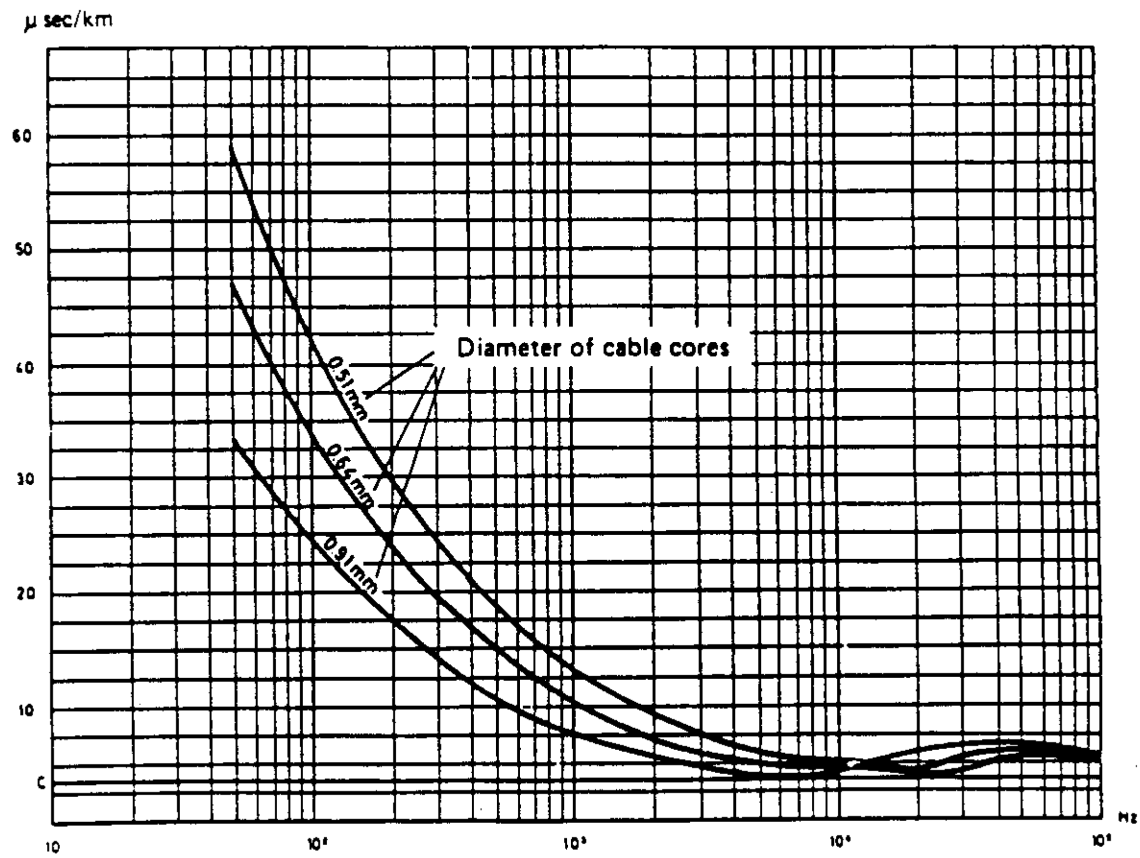
Loading coils are sometimes used to improve the frequency response of long lines reducing the bandwidth. These will, however, increase the transmission time of the signal and are therefore to be taken into account for teleprotection purposes.

In a protection system using pilot wires as a telecommunication medium it is essential to keep in mind the maximum permissible value of induced voltage in the event of the heaviest single phase to earth fault (with earthed systems) or cross-country fault (with isolated or quenched systems). The following precautions must be taken into account.



Attenuation versus frequency for cables

Figure 13.1



Group delay versus frequency for cables

Fig 13.2

Wherever practicable, the maximum spacing between pilot wires and power system conductors should be allowed at the design stage.

The design of the system from the point of view of induced voltage basically depends on the type of auxiliary circuits used (DC or AC).

The use of DC makes galvanic separation between the pilot wire and the stations impossible.

If, due to the constraints imposed upon the transmission system, a DC driving voltage cannot be employed, then AC transmission for the protection signal can be used. This has the advantage of permitting the use of isolating transformers, which help to keep the induced voltages away from the relays.

Pilot wire coupling with DC: In choosing the application of DC driving voltages, consideration has also to be given to the induced longitudinal voltages and ground potential rise. PTT regulations regarding the connection of different grounds have also to be taken into account. The sum of the effective induced longitudinal voltage and the ground potential rise in case of faults should not exceed approx. 1500 V with a safety margin. Very often the constraints imposed by these considerations may not allow full exploitation of the design limits from the point of view of relaying.

Pilot wire coupling with AC: For cases where the transmission is in AC, isolation transformers can be used. In these cases, the secondary of the isolating transformers must be insulated against earth for a value exceeding that of the effective ground potential rise and of the induced longitudinal voltage. This precaution takes into account the possibility of interruption in the earthing connection of the mid-point of the isolating transformers; the full induced voltage will be applied between the terminals and earth in case of a broken earth connection. Use of sparking gaps or lightning arrestors across the secondary winding is not a recommended practice since during a disturbance they may spark over and short circuit the signals when they are essential for selective protection. To reduce the circulating currents in the pilot-wire due to ground potential rise it may be necessary to separate the earth connections of the two extremities. This can be realized, for example, by terminating the shielding of the pilot-wire sufficiently away from the station (outside the ground potential rise flank), using a drainage coil and pulling the insulated pilot-wire cables in an insulated duct placed in a steel pipe which will carry the circulating currents resulting from the ground potential rise. With this arrangement it is not necessary to ground the mid-point of the isolating transformers at the station. This arrangement will also enable the use of pilot-wires of smaller cross-section since thermally they will be loaded only with the current resulting from the sum of the induced longitudinal voltage and the ground potential rise at the point of insertion of drainage coils. The screening effect of power system earth conductors, telecommunications or power cable sheaths and metallic ducts may be improved by effective earthing at their ends and intermediate points. Spare pairs within the cable may similarly be earthed to improve the screening effect, but in view of the small size of these conductors only a marginal improvement is likely at low frequencies.

Reliability is influenced by the design of the receiving equipment in relation to noise levels.

Noise is mainly due to lightning and to cross-talk from adjacent circuits within the cable. Noise due to line amplifying equipment is usually negligible. In the case of rented circuits, interruption may be caused by working parties. Although circuit failures can occur due to mechanical damage and ingress of moisture, reliability in this respect is generally good. Regular insulation testing if possible can detect slow deterioration of insulation and permit correction before failure occurs.

Supervision. In order to detect failure in the auxiliary circuit, it is common practice to provide means of supervising the continuity of the auxiliary circuit. Typical methods are a DC testing current continuously circulating or the use of a supervision audio or carrier frequency.

Performances. The advantages of using pilot wires are:

- High availability, mean time between failure (MTBF) in the order of 200,000 to 500,000 hours.
- Relatively low cost if the cable is also used for other purposes
- High reliability
- Little induction from power lines if separate routing is used.

The disadvantages are:

- High sensitivity to induced voltages in the event of power line faults and lightning strokes
- Buried cables are susceptible to breakage due to ground works
- Limited line lengths in order to maintain wide bandwidth and short transmission time
- Problems with the potential barrier at the border of the station earth network
- High cost of new cables, specially when they have to be buried

13.3 Power Line Carrier (PLC)

PLC is a telecommunication system using the power line as a transmission medium. Both overhead lines and cables can be used. Overhead line length of many hundreds of kilometres can be covered by one PLC link, whereas cable links can only cover distances up to about 100 to 150 kilometres. Lines with both overhead line sections and cable sections may be used, but each case has to be carefully investigated.

PLC is a telecommunication system peculiar to power lines and has been used for nearly 60 years. It is extensively used for HV and EHV lines. PLC equipment is very reliable with MTBF's in the order of 100 000 to 200 000 hours. The power line itself has also a very high availability, and if it is out of service for maintenance, normally there is no need for teleprotection. Even when the line is damaged due to line faults, the signal may pass the fault and reach the receiver due to the propagation characteristics of the signals. Phase-to-phase coupling is recommended. For line coupling characteristics see CIGRE and IEC publications.

Sometimes the PLC-equipment is exclusively used for command teleprotection schemes. Here the two positions are given as an on/off signal of a continuous signal (amplitude modulation), or as a frequency shift keyed (FSK) signal where the carrier is directly shifted with a deviation from 0.5 to 2 kHz (e.g. 100 kHz and 101 kHz when the shift is 1.0 kHz).

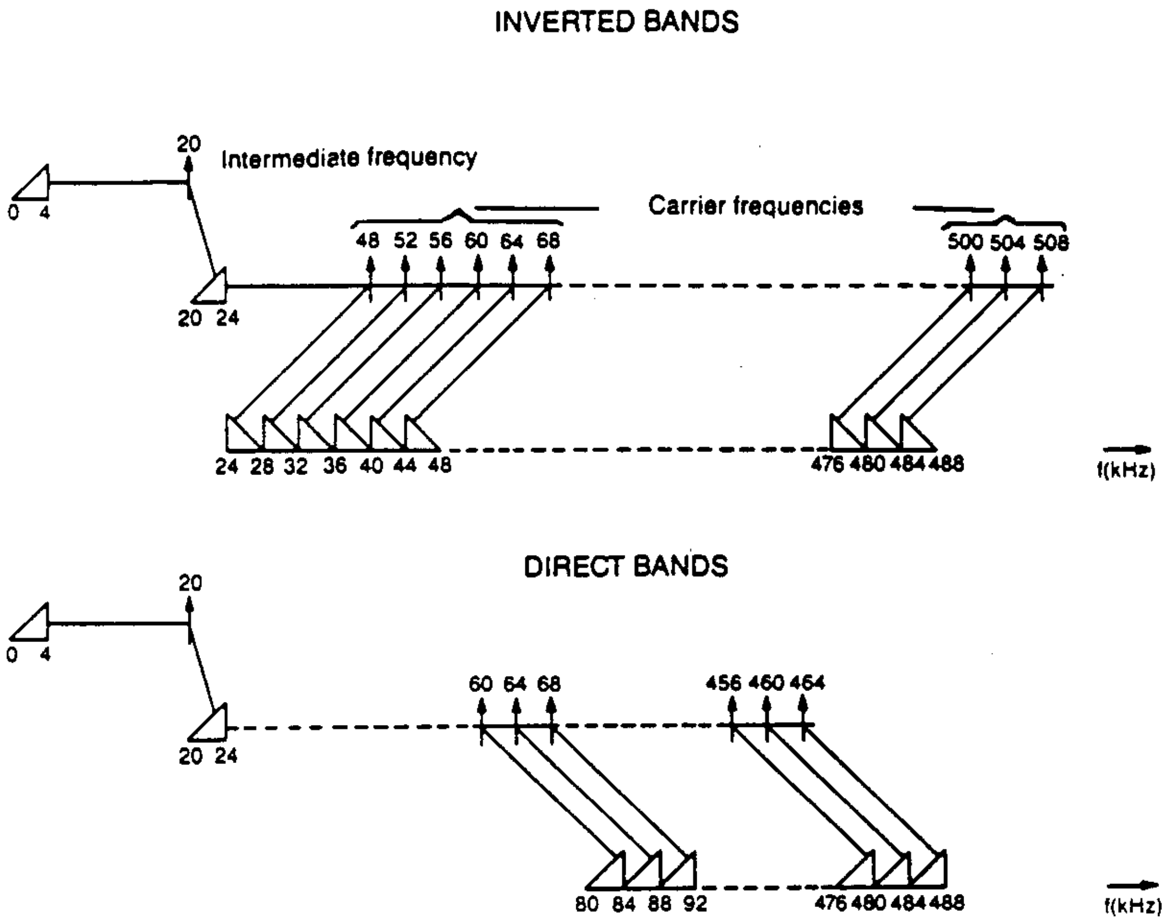
Both the PLC terminal and the coupling equipment to the line are normally situated within the switchyard and coupled to the main station earth. No problems with potential rise of the station earth towards remote earth during earth fault currents will therefore occur.

The carrier frequency range which can be used is normally between 40 and 500 kHz. For cable systems frequencies down to 20 kHz may be used. Part of the frequency range may be restricted in some countries in order to avoid interference with other services.

Normally only one band of 4 kHz is used, but two or more 4 kHz bands are also in use. For teleprotection purpose, multi 4-kHz bands equipment is not recommended because of the reduced signal-to-noise ratio.

The modulation is done in two steps. The first modulation is obtained using a fixed carrier of e.g. 20 kHz. One of the sidebands (and a reduced carrier) is transferred to the send frequency by modulation on another carrier frequency, see fig. 13.3. At the receiving end a similar procedure is used to restore the original low frequency band.

The modulated sideband normally consists only of one speech channel and superimposed frequency shift channels.



Frequency conversion plan for PLC-systems

Fig 13.3

The whole or part of the 4 kHz band can be used for teleprotection signals. For command systems only one or two frequency shift channels will be used, whereas analogue systems like phase-comparison may use the whole band.

Due to the special conditions required by the power line, the PLC equipment must meet special requirements regarding Signal-to-noise (S/N)-ratio and maximum attenuation which are not normally necessary for other carrier frequency equipment for telephone purposes.

The parameters influencing PLC communication are the background corona noise, the impulsive noise and the additional attenuation in case of flash over.

The background noise, due to corona discharge, severely limits the maximum permissible span of the line (for a given S/N ratio) specially if related to certain limitations on maximum transmitted power existing in the majority of countries for protection against possible interference.

The impulsive noise, due to operation of isolators and circuit breakers or lightning strokes, etc, is so strong that the useful signal cannot overcome it. This means that this kind of noise can simulate a useful signal which was not transmitted or can mask a useful signal which was transmitted.

Moreover the effect of impulsive noise may be reinforced by the additional attenuation of the communication link in case of flashover between phases or phases and earth which establishes a short circuit on the phases used for transmission of signals.

Some of these disadvantages can be overcome by special design of the PLC communication link and the teleprotection equipment (see also chapter 12).

Normal implementations include power boosting of the teleprotection signal when needed and use of phase-to-phase coupling in order to guarantee the reception of the signal also in presence of phase to ground faults on the power line.

The high noise level due to corona losses depends on the line construction, the line voltage and weather conditions. The corona noise is always present and special precautions must be taken to obtain a reasonable S/N ratio at the receiver side for all weather conditions. In fact this noise may vary 20-30 dB on the same line depending on weather conditions.

The noise will increase with the line length and decrease with frequency (see IEC publication 663).

If S/N-ratios smaller than those given as minimum figures occur, there will be problems both for the speech channel, the data channel and sometimes for the teleprotection channels. This is mostly the case with phase-comparison systems which may be vulnerable to a low S/N-ratio. The command teleprotection systems are often secured by a form of blocking so that a command is prohibited when the S/N-ratio decreases.

Impulsive noise from isolator operation, circuit breaker operation, lightning and noise from power line faults will give much higher noise amplitudes with very high noise spikes. This noise, however will last only a short time, for circuit breaker operation only in the order of 20 ms, for lightning up to 1000 ms. The high noise level caused by a power line fault will last only 2 to 10 ms, while an isolator operation noise may last for 500 to 5,000 ms.

This noise will be attenuated on the power line like that of the PLC-signal. When the noise is passing through a station, the attenuation will vary from 10 to 40 dB, depending on the power system configuration. Because of the high level, this noise may influence equipment in stations far away from the origin of the noise.

The time the noise is present is, however, very short and is not continuous, but impulsive. Therefore it is possible to build teleprotection equipment which will sustain this noise and be very secure and dependable, preventing false operation.

The onset of a power line fault will create a high noise, lasting 2 to 10 ms. When the fault arc is established, the noise will diminish drastically. At the same time the line attenuation will increase due to the short circuit of the line by the fault arc.

The length of a power line using PLC will vary from short lines of 10 to 20 km to long lines of many hundreds of kilometres. The difference in line attenuation due to the line length, the line construction and the transmitted high frequency used can therefore be considerable.

The line attenuation will also vary from time to time depending on the weather conditions. Rain, fog, dust, sand and salt will influence the attenuation. Icing of the conductors especially will cause heavy additional attenuation up to 5 to 10 times (in dB) the normal attenuation for the line section involved by icing.

These varying conditions lead to transmitters with different output powers ranging from 2 watts to 250 watts peak envelope power (PEP). The most commonly used transmitters will have output powers of 10 to 40 watts. (PEP)

The propagation of a signal on a three phase power line may be explained by the combined signals of three different modes which, each, propagates with a certain loss and velocity.

For normal weather conditions the line attenuation of carrier signals on overhead power lines is generally in the region of 0.02 to 0.2 dB/km. The attenuation will depend on the line construction and the frequency used and will increase with frequency.

For normal weather conditions the S/N-ratio will be 10 to 20 dB better than for adverse weather conditions. For design purpose one should try to avoid the minimum values.

For a power line fault, where one or more phases are earthed or short circuited, the line attenuation will increase when the fault arc is established.

The majority of all power line faults are single phase to ground faults. A phase-to-phase coupling (see figure 13.4) may therefore be more secure and give smaller additional losses than a phase-earth coupling. A phase-to-phase coupling can either be done between two phase-conductors in one circuit or between one conductor in one circuit and another conductor in a second circuit (Intercircuit coupling). This can only be done when the two circuits are run on the same towers. A phase-earth coupling uses only one line trap, one coupling capacitor, one phase-earth coupling device, and no hybrid transformer at each station.

Most of the power line faults will give an additional attenuation in the order of 10 to 15 dB, but a line fault near to the line end and three-phase faults may give additional losses as high as 30 dB and even higher. Special precautions to handle this attenuation have to be taken, to ensure reliable operation for the teleprotection equipment during all sorts of power line faults.

When a power line fault starts, the induced noise level is very high for a period of 2 to 10 ms. This noise may prevent all signalling along the line. When the fault arc is established, the noise level falls drastically, by something like 40 dB. With sufficient signal power for bridging the increased line attenuation, reliable signalling through the fault is possible. Additional power for a teleprotection command signal is often obtained by boosting the teleprotection signal by about 5 to 15 dB.

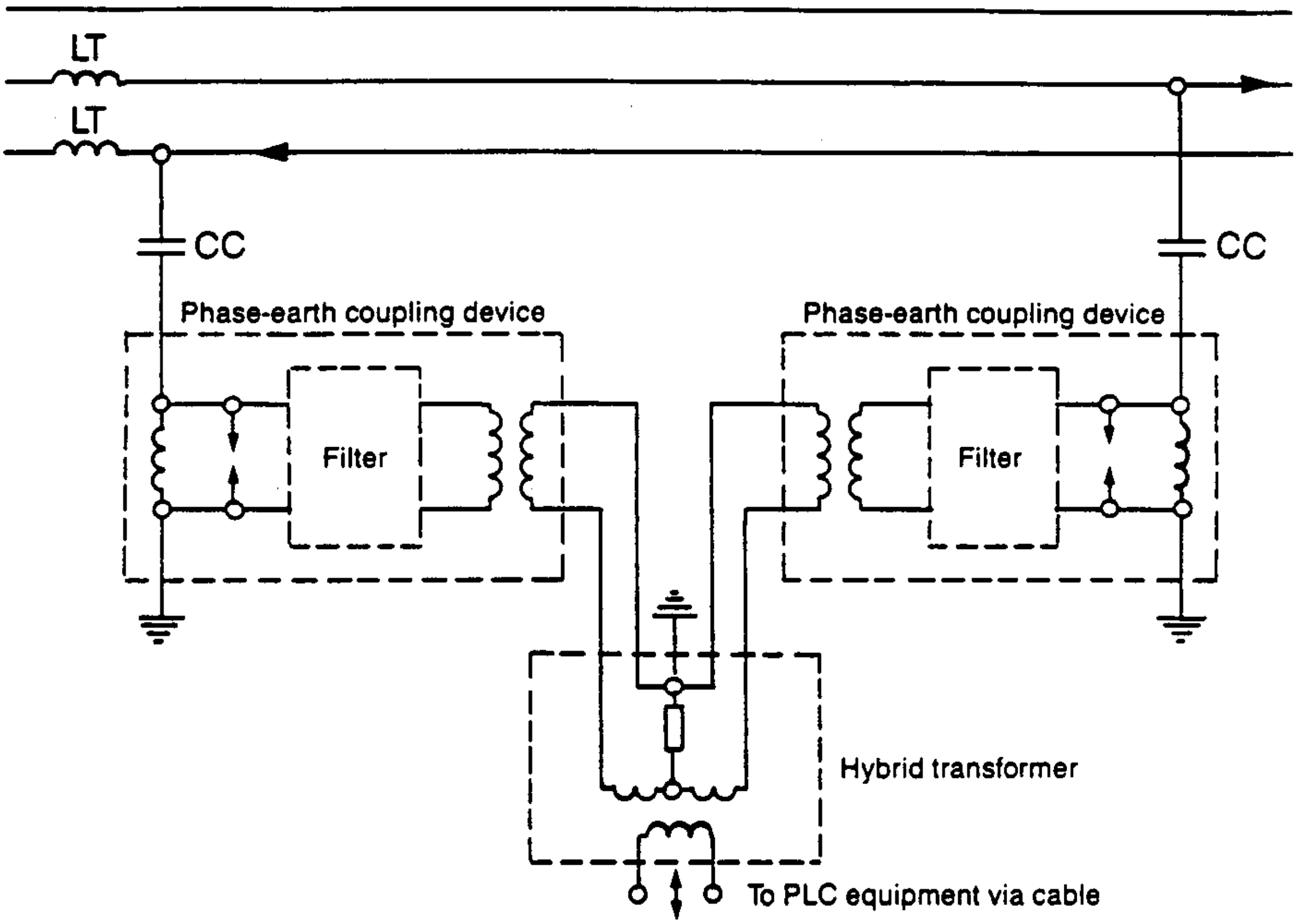


Fig 13.4 Example of phase-phase line coupling

Performances

The advantages of the PLC communication link used for teleprotection are:

- The overhead power line is normally a very reliable transmission medium

- Long distances, many hundreds of kilometres can be covered by each link
- Transmission takes place between the two stations which are interconnected for teleprotection purpose
- The equipment is situated at the power station, giving easy access for control and maintenance
- PLC equipment is reliable with a high MTBF (100, 00 to 200, 000 hours)

The disadvantages are:

- High impulsive noise level generated created by line faults, lightning and isolator breaker operation.
- Limited frequency band available. This limits the number of PLC-links that can work within a given network.
- Limited bandwidth (4 kHz) restricting the minimum transmission time for a teleprotection command system to appr. 5 ms.
- Additional attenuation in case of line faults
- Limited power due to national regulations.

13.4 Radio links

Radio links used for teleprotection purpose are links between two fixed points the two stations at the end of a power line transmitting signals normally in both directions at the same time (full duplex working). Mobile radio systems are not used for teleprotection as they are normally simplex working, e.g. one direction only at a time.

The principal characteristic for which radio links are chosen is that they are not influenced by electrical faults and that they can operate during fault occurrence without degradation of their performances.

Radio links, moreover, permit the use of large bandwidth systems and are therefore used in conjunction with analog protection systems which require the transmission of a large amount of information per unit of time.

Radio links are often used, national regulations permitting, when it is economically beneficial or when PLC links do not offer the necessary channel capacity. PLC and radio links are also often used as back up systems for each other.

The link between two power stations can either be realized as a single hop or by multiple hops using repeater stations. Repeaters are used when there is no direct sight between the terminals or if the distance is too great for a one hop link.

14 APPENDIX

Defining security for a command teleprotection equipment.

"Guide for planning of power system telecommunication networks" published by CIGRE SC 35 in 1986? gives in appendix B an explanation of a noise model for PLC-systems. This noise model is presented here in figure 14.1.

The curve b of figure 14.2 gives the probability of unwanted commands per 200 ms noise burst for a teleprotection receiver. Curve c is the same when a noise blocking device is acting at S/N = -7 dB (for noise bandwidth of 4 kHz).

The curve a is the noise model adjusted to the same S/N-ratios as for the other curves. The probability of noise is changing and for the most important situation will vary between 10^{-4} and 10^{-5}. The probability of unwanted commands per 200 ms noise burst will vary from very low values at S/N = -5 dB up to about 10^{-2} without noise blocking device and to $4 \cdot 10^{-7}$ at S/N = -7 dB when noise blocking device is used.

When multiplying the values from the curves a and c and integrating the result, the total probability of unwanted commands per 200 ms noise burst will be

$$P_{UC} = \underline{5,2 \cdot 15^{-11}}$$

In one year there are:

$A = 5 \cdot 60 \cdot 60 \cdot 24 \cdot 365 = 1.58 \cdot 10^8$ 200 ms noise bursts.

The probability of having one unwanted command per 200 ms noise burst in one year is therefore:

$$\underline{P_{UCyear}} = \frac{1}{1.58 \cdot 10^8} = \underline{6.33 \cdot 10^{-9}}$$

$P_{UC} = 5.2 \cdot 10^{-11}$ means that there will be a probability of

$$P_{UC} = \frac{5.2 \cdot 10^{-11}}{6.33 \cdot 10^9} = 0.833 \cdot 10^{-2} \text{ unwanted commands per year.}$$

or $\frac{1}{0,823 \cdot 10^2}$ = 122 years between each unwanted command.

This is a statistical figure, but gives a good idea of the security.

In addition to attenuation caused by fading, the higher frequencies are influenced by attenuation due to weather conditions like rain and fog.

These two drawbacks can be overcome by properly designing the link. The position of intermediate repeaters, the power of the transmitters and the shape of antennas have also to be chosen properly.

Moreover an improvement in the design, in order both to add security against the aforesaid impairments and to increase availability of the link, is possible through redundancy, using double radio equipment and double antenna.

The "diversity" of radio links is obtained by this double apparatus configuration. Space diversity is obtained if different antennas are located in different positions on the antenna mast while frequency diversity is obtained if different frequencies are used for the two transmitters.

Naturally on the receiving side the signals coming from different antennas are combined in order to obtain at the output the best possible signal. Both types of diversity, used separately or at the same time, take care of multiple reflections on ground, obstacles and ionized atmosphere permitting to limit the outage time of the link in the worst month.

Normally the ratio outage time/total time of service is about 10^{-4}-10^{-5} in the worst month.

If the two stations at the end of a power line can be linked by a single hop radio link, this is a good and economical way of solving the requirements for information capacity between these two stations.

When repeater stations have to be implemented, the cost of the whole link will increase. The reliability will also be somewhat less. When a repeater station may have difficult access or even be impossible to access during parts of the year due to climatic conditions, this also has to be taken into account at the design stage.

Performances

The advantages of radio links are:

- Greater bandwidth
- High reliability with MTBF in the region of 100, 000 to 200, 000 hours.
- The transmission of information is not normally influenced by induced noise from the power network due to faults. Conversely, fading is not caused by any fault on the network and so there is no influence on the protection system.

- The transmitter and receiver are normally situated within the stations earth network and problems due to earth potential rise against outside world do not to be taken into account.

- The control and maintenance of the equipment is easily done since all the equipment normally is situated within the power station when only one hop is used.

The disadvantages are:

- Unless very good margin is provided, fading will occur breaking the link for short parts of the time during the year.

- Problem of getting line-of-sight both for one hop and multihop links.

- Cost will increase and reliability will decrease when multihop links have to be used.

- If a transmitter or a receiver has to be placed outside the stations earth network, then the problem of getting the cable connection into the station will remain.

13.5 Fibre Optic links

General

In the telecommunication systems for electricity power supply authorities, the employment of carrier frequencies on cables, power line carrier systems and multi-channel microwave radio have proved their worth for many years and are absolutely indispensable.

At present fibre optics is increasing its importance due to its special properties, e.g. no interference from other communication systems and no influence by the electrical environment.

An optical fibre used for communication purpose is normally a very thin glass fibre (outer diameter 100 to 200 um) made of a material which has low attenuation for light waves travelling inside the fibre. At the moment very pure silica glass is used, but research on other materials is in progress.

The fibre acts as a tube where the light travelling inside the tube is totally reflected at the wall of the tube.

The tube is made of a core of glass surrounded by a cladding of glass with slightly lower refraction index than the core. The total reflection is due to this change in the refraction index.

An optical transmission link consists, as Fig. 13.5 shows, essentially of an optical transmitter, a light-guiding fibre as transmission medium and an optical receiver. Either light-emitting diodes (LED's) or semiconductor lasers are used as transmitting elements.

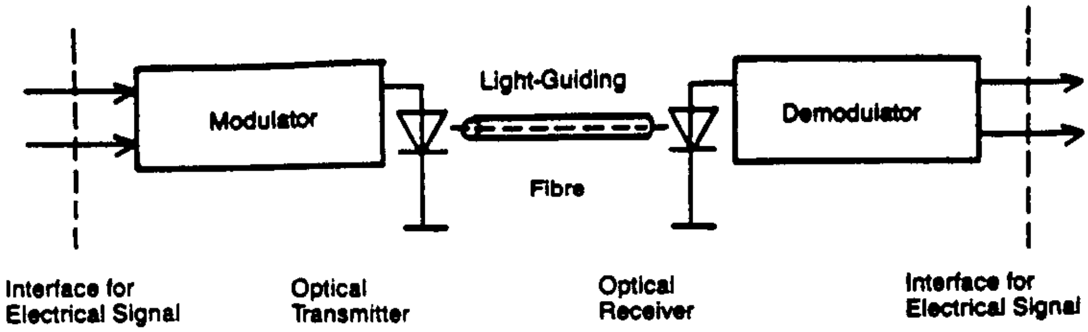


Fig 13.5 Example of an optical transmission link

Fibre characteristics

Two types of optical fibres are used at the moment. The outer diameter, for all of them, is between 100 and 200 um. The diameter and the structure of the core will, however, vary as shown in fig 13.6 and explained in the following.

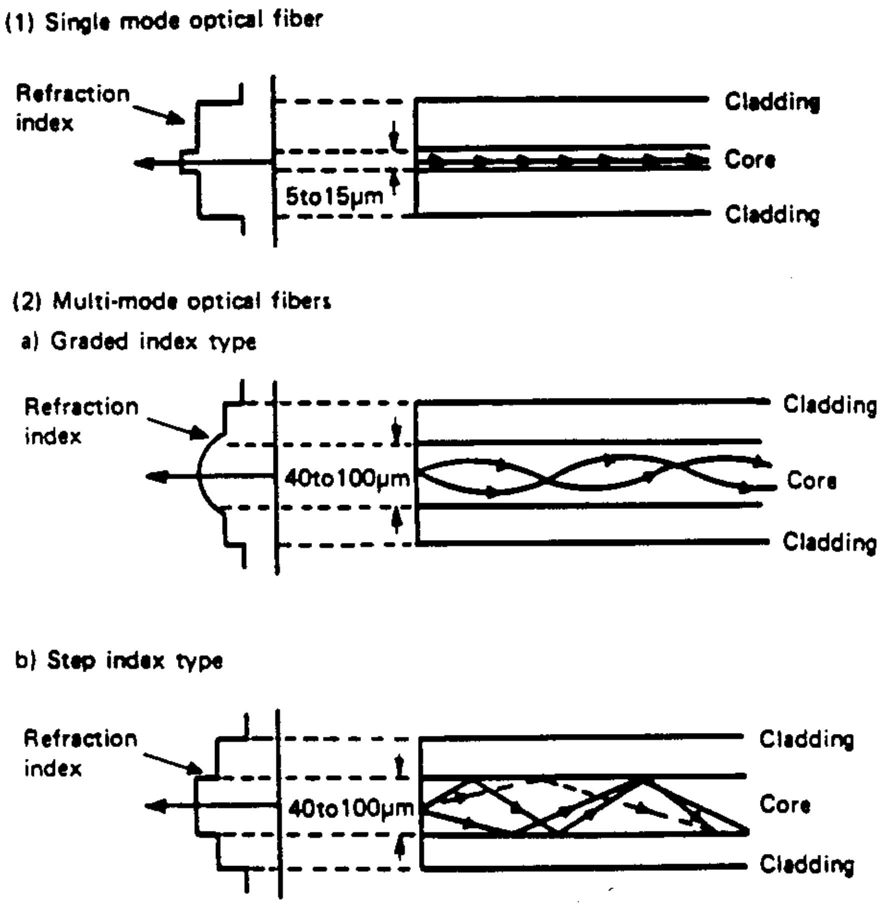


Figure 13.6 Optical fibre types

1) Single mode (monomode) fibre.
The core diameter is very small and is between 5 and 15 um. Within this fibre only one transmission mode will propagate as can be seen from the figure.

2) Multimode fibre which have two different implementations

a) Graded index type.
The core diameter is between 40 to 100 um. The refraction index will vary within the core as given in the figure. This will force the light-rays to bend towards the centre of the core.

b) Step index type.
The core diameter is the same (between 40 to 100 um). The different transmission modes will be reflected at the wall of the core.

The attenuation of the light waves through the fibre core depends on the core material and on the wavelength of the light wave. The material now used (silica glass) has an typical attenuation curve like that shown in figure 13.7. Two attenuation minima are seen at appr. 1.3 um and 1.55 um. The wavelength mostly used in the first generation of equipment is 0.85 um because light emitters and receivers are more stable and cheap for this wave length. Emitters and receivers suitable for 1.3 um are also on the market now. This wavelength is used in the second generation equipment.

The transmission window at 1.55 um with attenuation as low as 0.2 to 0.3 dB/km will be very interesting for long lines.

Research is being carried out on other fibre materials which will give only fractions of the attenuation of todays fibres.

Attenuation constants for todays fibres are:

for 0.85 um wavelength, 2 to 5 dB/km
" 1.3 um " , 0.5 to 1.5 dB/km
" 1.55 um " , 0.2 to 0.5 dB/km

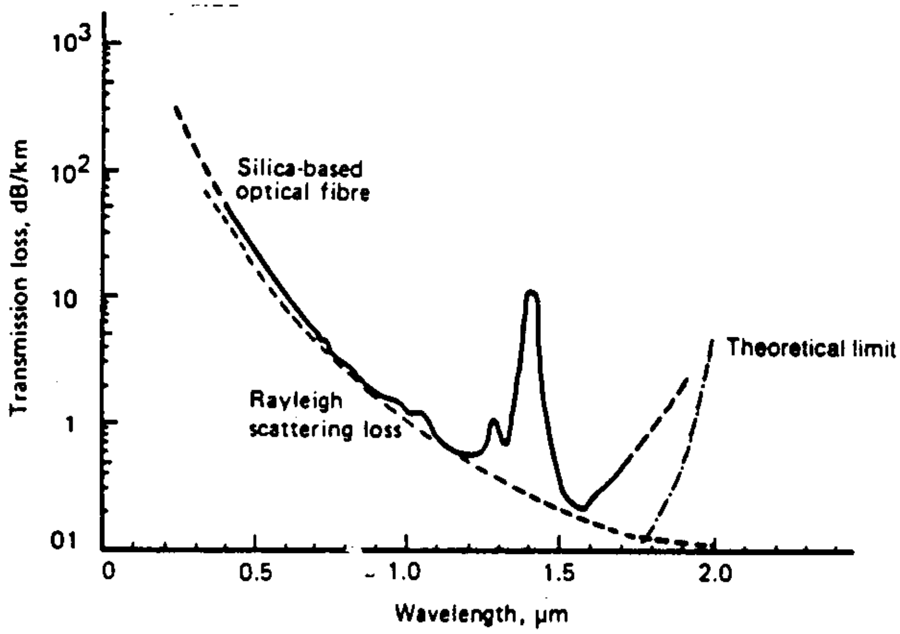


Fig 13.7 Attenuation constant for optical fibre

a) Material (Chromatic) dispersion

The light used for transmission on the fibre will have a certain spectral width. That means that the light signal will contain a spectrum of signals with wavelengths around the main light wave. These signals with different wavelengths will travel with different speeds and thus arrive at different time at the receiver. A squarewave pulse sent from the transmitter, will therefore arrive at the receiver as a more broadened and flattened pulse, see figure 13.8.

The 1.3 um wavelength has an other advantage beside that of a low attenuation constant. The material dispersion is practically cancelled at this frequency.

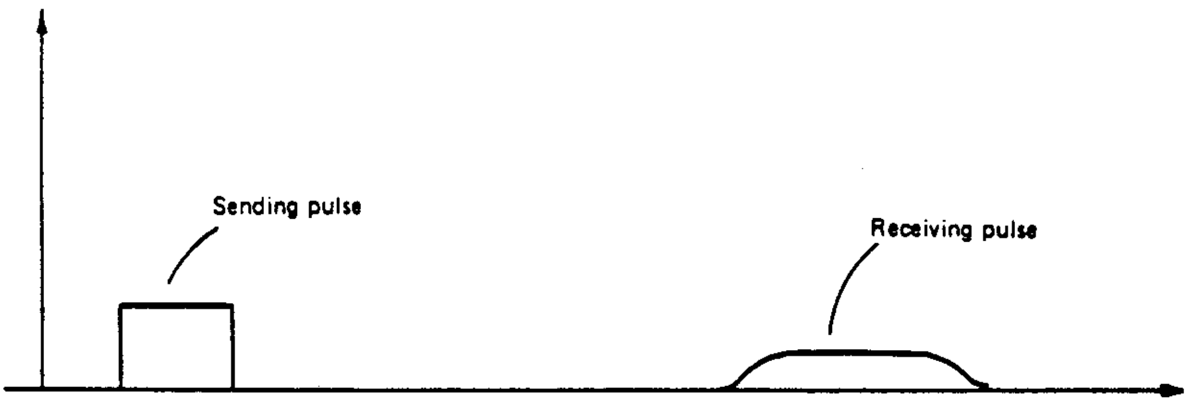


Fig 13.8 Dispersion of a light pulse

b) Modal dispersion

This is caused by the different modes of the light waves which will travel by different paths through the fibre. The different modes will therefore reach the receiver at different times, causing dispersion.

Modal dispersion can be avoided by using single-mode fibre. Graded index fibre where the velocity of the light waves depends on the refraction index of the core will also minimise this dispersion.

The light waves are not travelling at the speed of light (C) inside the fibre, but at 0.6 to 0.7 · C.

Two main systems are normally dealt with: attenuation or power limited and dispersion limited systems.

The attenuation constant of the fibre, the attenuation of the joints, the transmitter power and the sensitivity of the receiver can restrict the line length which can be covered. This system is power limited.

Distortion will occur when the received pulses interfere as in figure 13.9 and form a dispersion limited system. To avoid this, an upper pulse repetition frequency (minimum distance between sending pulses) has to be given. A figure for the MHz · km is therefore given for each fibre type, as an indication of these two types of limitation.

The product MHz · km shows the extent of a transmission band. For example an optical fibre having a figure of 100 MHz · km means that the amplitude of an optical signal having been modulated at 100 MHz is reduced to a half (6 dB attenuation) when the signal is propagated for 1 km.

Typical bandwidth figure for different fibre types are as follows:
single mode : up to 50 GHz·km
multimode, graded index: 200 to 1000 MHz·km
step index : 10 to 100 MHz·km

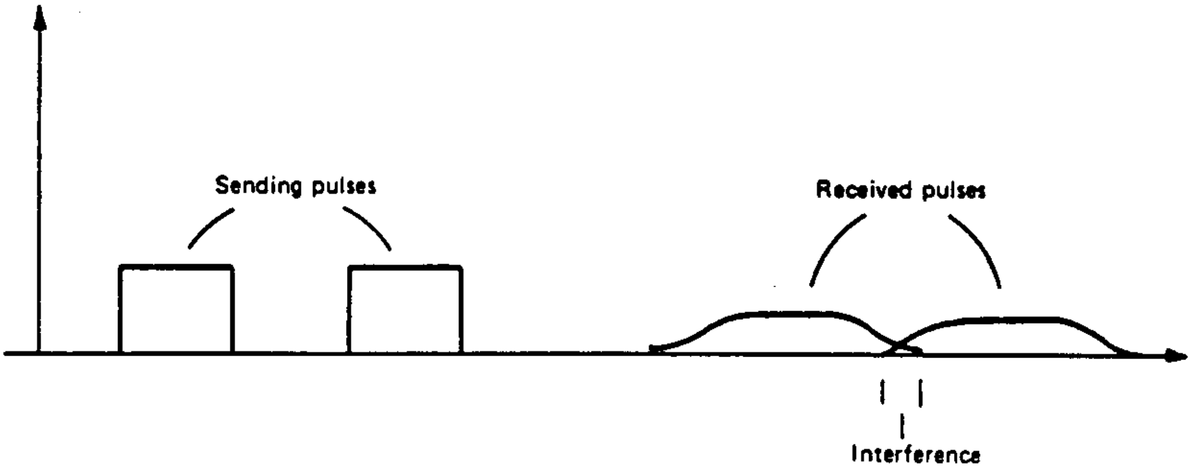


Fig 13.9 Interferring received pulses

Optical Elements

Semiconductor light sources can be considered exclusively as optical transmitters for fibre optic transmission links. These are diodes which emit light when current is passing through them in the current flow direction, whereby the light intensity is directly modulated by the driving current of the information to be transmitted.

Among semiconductor light sources, one distinguishes between incoherently radiating light-emitting diodes (LEDs) and coherently radiating laser diodes. Their basic characteristics are depicted in Fig. 13.10. The LED radiates with an optical power proportional to the driving current and is therefore suited for transmission of digital as well as for analogue signals.

In contrast to that, the light power of a laser diode increases steeply above the so called threshold current. This makes it particularly suitable for transmission of digital signals. Another essential difference between LEDs and laser diodes lies in their radiating characteristics.

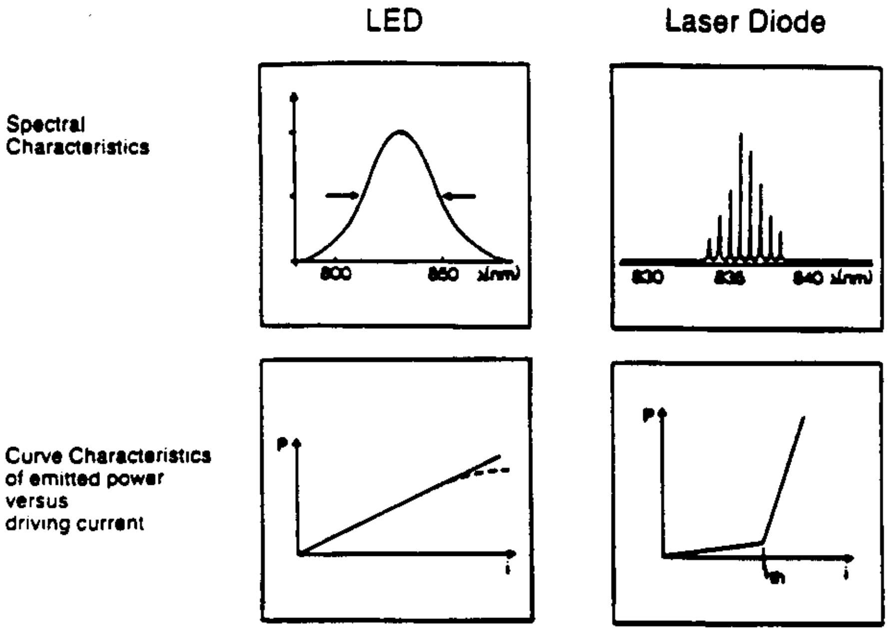


Fig 13.10 Optical transmitting elements

The incoherently radiating LED emits light scattered within the entire solid angle, while the laser puts out coherently directed radiation. With such a characteristic, the radiation of a laser may be coupled into the light-guiding fibre at a higher efficiency.

LEDs radiate incoherent light at a relatively large spectral width of about 50nm, while semiconductor lasers emit coherent light at a spectral width of about 3nm.

Because of its higher output power and better coupling efficiency, the light power level injected by a laser diode into a light-guiding fibre is several orders of magnitude (10 to 30 dB) higher than that injected by a LED, and correspondingly longer transmission distances can be spanned without repeaters. Because of these characteristics, LEDs are used largely in transmission systems over short distances (about 1 km) with analogue or digital signal transmission at bit rates up to 10 Mbit/s, while lasers find application as transmitting elements for long-haul communication systems. The laser diode has a very low spectral width and will therefore give small material dispersion.

Semiconductor detectors are available as optical receivers for fibre optic transmission links. Silicon semiconductors, such as PIN diodes and avalanche photo diodes, which are well matched to the wave length of transmitters, are preferably used. Photo diodes possess high spectral sensitivity and fast response time, and are capable of detecting signals with a light power of a few nW and a bandwidth of up to a few GHz. PIN photo diodes without internal current amplification, require light power of about 1 nW for sufficiently precise detection. For avalanche photo diodes with internal current amplification, the optical power required is reduced by a factor of about 10.

Modulation and Demodulation

Analogue and digital modulation are used in fibre optic communication systems, but this refers to the form of modulation used in converting information into an electrical signal. The intensity of the optical signal is changed in accordance to this modulated electrical signal.

On the receiving side, an electrical signal is obtained when an optical signal - having been weakened and distorted through optical fibre propagation - is received by a light receiving element.

This baseband signal is the output after the amplification and regeneration of the signal from the information source.

For long lines regenerators must be used. A regenerator consists of a light receiver, an electrical regenerator and a light emitter. The light receiver will transform the receiver light pulses into electrical pulses. These pulses will be reshaped in the regenerator. The reshaped pulses will modulate the light emitter which will send the reshaped and amplified light-pulses on to the next fibre section. The regenerator needs a separate electric power supply.

Implementation

A fibre optic link will consist of the fibre cable, the light emitter and light receiver and the electrical modulation and demodulation equipment at the send and receive side. The task of the interface equipment is to transform the analogue signals (i.e. speech) or digital signals (i.e. protection signals and data signals) into a suitable format for modulating the lightwave. Although it is possible to modulate the light wave with analogue signals directly, this is rarely used, as the electro-optical converters are non-linear. Normally all signals are converted to digital signals.

Analogue signals are transformed to pulse-code modulated (PMC) signals or to pulse frequency modulated signals or to pulse width modulated signals.

Multi-condition digital signals have to be transformed to two-condition signals, since only two conditions (0 and 1) can be used for light pulses.

In respect of the MHz · km figure the broad band of signals allows for many hundreds of speech, data and protection channels to be transmitted at the same time over one fibre. At present power utilities only need a limited number of channels. Therefore only the fibre attenuation will be the limiting factor in the MHz · km figure.

Performances

A very high reliability can be built into a communication link. A bit error rate of 10^{-11} has been achieved. For teleprotection channels a very high security may be obtained since no electrical disturbances will occur. The transmission time will also be very short, in the order of some milliseconds, since a very broad frequency band can be used. The immunity from electrical distubances makes fibre optics very useful for communication inside a power station, and for communication from a power station to the surrounding world through the potential barrier of the power station.

The advantages of fibre optic links are:

- Absolute insensitivity to electric and magnetic interference fields, produced by isolator sparks, corona discharge, lightning, radio transmitters etc,
- Absolute potential isolation between high-voltage equipment and telecommunication equipment.
- No crosstalk problems
- Large bandwidth
- High transmission speed
- Extraordinarily low bit error rate

The disadvantages are:

- For long distances, repeaters have to be used
- A break in the fibre will result in the loss of a huge amount of information
- Installation costs as for telecommunication cables

14 APPENDIX

Defining security for a command teleprotection equipment.

"Guide for planning of power system telecommunication networks" published by CIGRE SC 35 in 1986? gives in appendix B an explanation of a noise model for PLC-systems. This noise model is presented here in figure 14.1.

The curve b of figure 14.2 gives the probability of unwanted commands per 200 ms noise burst for a teleprotection receiver. Curve c is the same when a noise blocking device is acting at S/N = -7 dB (for noise bandwidth of 4 kHz).

The curve a is the noise model adjusted to the same S/N-ratios as for the other curves. The probability of noise is changing and for the most important situation will vary between 10^{-4} and 10^{-5}. The probability of unwanted commands per 200 ms noise burst will vary from very low values at S/N = -5 dB up to about 10^{-2} without noise blocking device and to $4 \cdot 10^{-7}$ at S/N = -7 dB when noise blocking device is used.

When multiplying the values from the curves a and c and integrating the result, the total probability of unwanted commands per 200 ms noise burst will be

$$P_{UC} = \underline{5{,}2 \cdot 15^{-11}}$$

In one year there are:

$A = 5 \cdot 60 \cdot 60 \cdot 24 \cdot 365 = 1.58 \cdot 10^8$ 200 ms noise bursts.

The probability of having one unwanted command per 200 ms noise burst in one year is therefore:

$$\underline{P_{UCyear}} = \frac{1}{1.58 \cdot 10^8} = \underline{6.33 \cdot 10^{-9}}$$

$P_{UC} = 5.2 \cdot 10^{-11}$ means that there will be a probability of

$$P_{UC} = \frac{5.2 \cdot 10^{-11}}{6.33 \cdot 10^{9}} = 0.833 \cdot 10^{-2} \text{ unwanted commands per year.}$$

or $\frac{1}{0{,}823 \cdot 10^{2}}$ = 122 years between each unwanted command.

This is a statistical figure, but gives a good idea of the security.

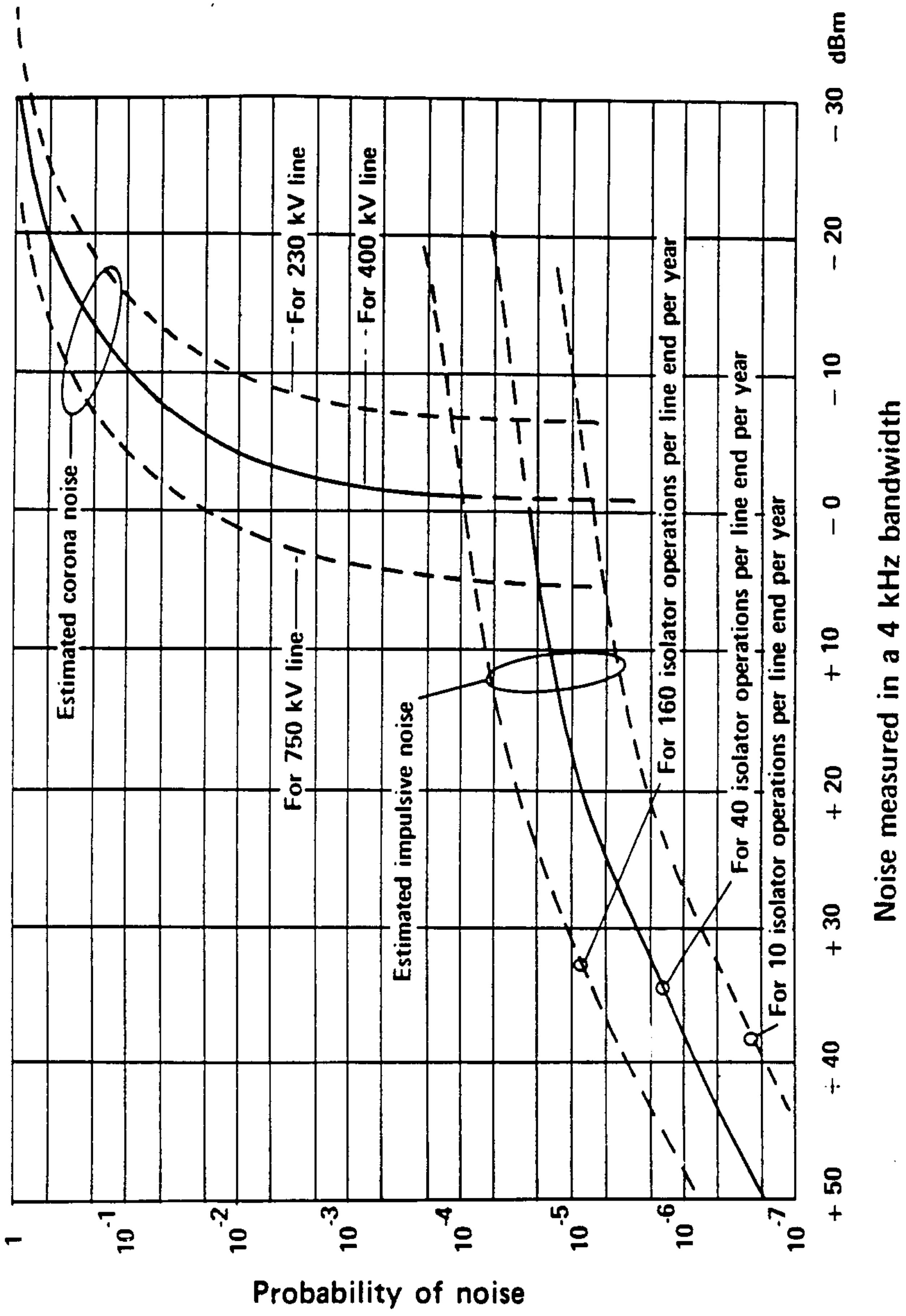


Fig 14.1 Noise model for PLC systems

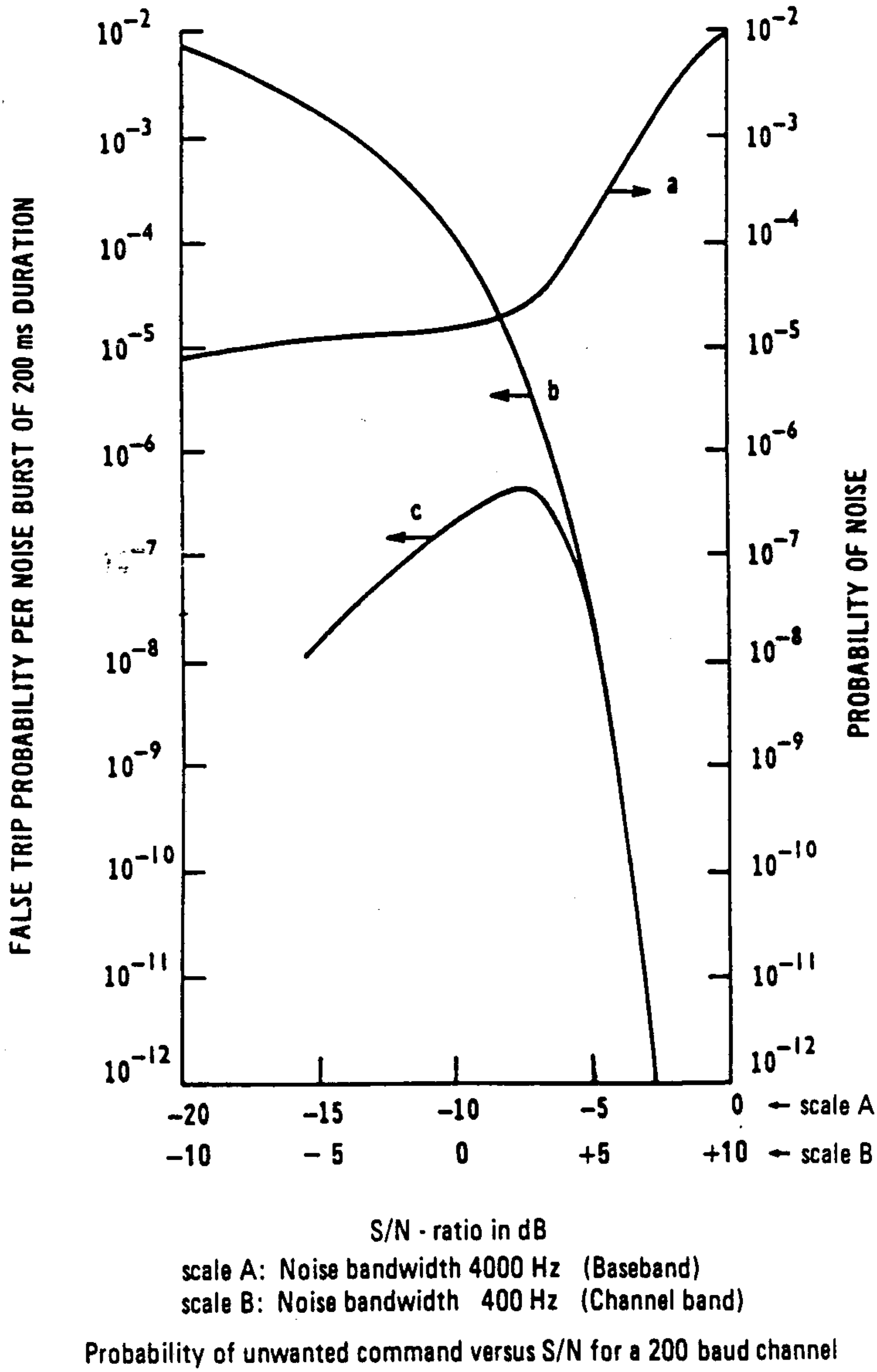


Fig 14.2 Probability of unwanted command versus S/N for a 200 baud channel

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