# • 13 • Protection of Complex Transmission Circuits

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## 13.1 INTRODUCTION

Chapters 10-12 have covered the basic principles of protection for two terminal, single circuit lines whose circuit impedance is due solely to the conductors used. However parallel transmission circuits are often installed, either as duplicate circuits on a common structure, or as separate lines connecting the same two terminal points via different routes. Also, circuits may be multi-ended, a three-ended circuit being the most common.

For economic reasons, transmission and distribution lines can be much more complicated, maybe having three or more terminals (multi-ended feeder), or with more than one circuit carried on a common structure (parallel feeders), as shown in Figure 13.1. Other possibilities are the use of series capacitors or direct-connected shunt reactors. The protection of such lines is more complicated and requires the basic schemes described in the above chapters to be modified.

The purpose of this chapter is to explain the special requirements of some of these situations in respect of protection and identify which protection schemes are particularly appropriate for use in these situations.

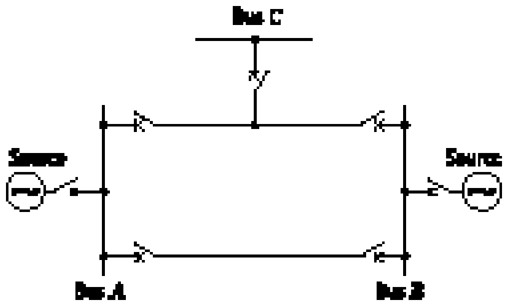

Figure 13.1: Parallel and Multi-ended feeders

## 13.2 PARALLEL FEEDERS

If two overhead lines are supported on the same structures or are otherwise in close proximity over part or whole of their length, there is a mutual coupling between the two circuits. The positive and negative sequence coupling between the two circuits is small and is usually neglected. The zero sequence coupling can be strong and its effect cannot be ignored.

The other situation that requires mutual effects to be taken into account is when there is an earth fault on a feeder when the parallel feeder is out of service and earthed at both ends. An earth fault in the feeder that is in service can induce current in the earth loop of the earthed feeder, causing a misleading mutual compensation signal.

### 13.2.1 Unit Protection Systems

Types of protection that use current only, for example unit protection systems, are not affected by the coupling between the feeders. Therefore, compensation for the effects of mutual coupling is not required for the relay tripping elements.

If the relay has a distance-to-fault feature, mutual compensation is required for an accurate measurement. Refer to Section 13.2.2.3 for how this is achieved.

### 13.2.2 Distance Protection

There are a number of problems applicable to distance relays, as described in the following sections.

#### *13.2.2.1 Current reversal on double circuit lines*

When a fault is cleared sequentially on one circuit of a double circuit line with generation sources at both ends of the circuit, the current in the healthy line can reverse for a short time. Unwanted tripping of CB's on the healthy line can then occur if a Permissive Over-reach or Blocking distance scheme (see Chapter 12) is used. Figure 13.2 shows how the situation can arise. The CB at $D$ clears the fault at $F$ faster than the CB at $C$. Before CB $D$ opens, the Zone 2 elements at $A$ may see the fault and operate, sending a trip signal to the relay for CB $B$. The reverse looking element of the relay at CB $B$ also sees the fault and inhibits tripping of CB's $A$ and $B$. However, once CB $D$ opens, the relay element at $A$ starts to reset, while the forward looking elements at $B$ pick up (due to current reversal) and initiate tripping. If the reset times of the forward-looking elements of the relay at $A$ are longer than the operating time of the forward-looking elements at $B$, the relays will trip the healthy line. The solution is to incorporate a blocking time delay that prevents the tripping of the forward-looking elements of the relays and is initiated by the reverse-looking element. The time delay must be longer than the reset times of the relay elements at $A$.

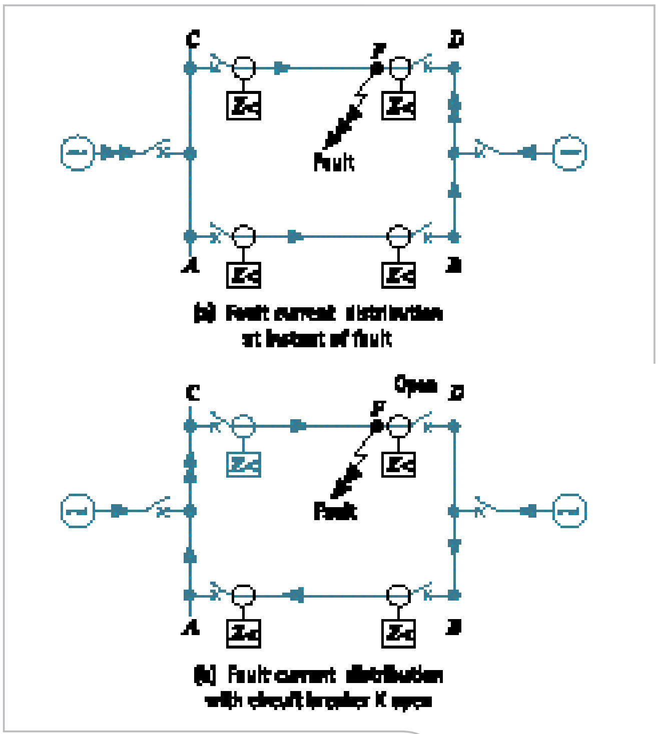

*Figure 13.2: Fault current distribution in double-circuit line*

#### *13.2.2.2 Under-reach on parallel lines*

If a fault occurs on a line that lies beyond the remote terminal end of a parallel line circuit, the distance relay will under-reach for those zones set to reach into the affected line.

Analysis shows that under these conditions, because the relay sees only 50% (for two parallel circuits) of the total fault current for a fault in the adjacent line section, the relay sees the impedance of the affected section as twice the correct value. This may have to be allowed for in the settings of Zones 2 and 3 of conventionally set distance relays.

Since the requirement for the minimum reach of Zone 2 is to the end of the protected line section and the under-reach effect only occurs for faults in the following line section(s), it is not usually necessary to adjust Zone 2 impedance settings to compensate.

However, Zone 3 elements are intended to provide backup protection to adjacent line sections and hence the under-reaching effect must be allowed for in the impedance calculations.

#### *13.2.2.3 Behaviour of distance relays with earth faults on the protected feeder*

When an earth fault occurs in the system, the voltage applied to the earth fault element of the relay in one circuit includes an induced voltage proportional to the zero sequence current in the other circuit.

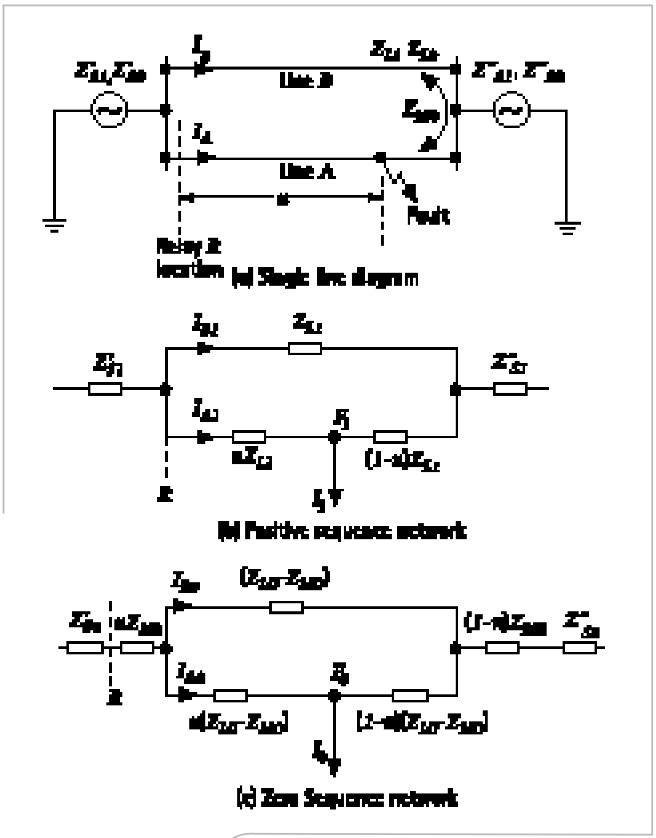

Figure 13.3: General parallel circuit fed from both ends

As the current distribution in the two circuits is unaffected by the presence of mutual coupling, no similar variation in the current applied to the relay element takes place and, consequently, the relay measures the impedance to the fault incorrectly. Whether the apparent impedance to the fault is greater or less than the actual impedance depends on the direction of the current flow in the healthy circuit. For the common case of two circuits, $A$ and $B$, connected at the local and remote busbars, as shown in Figure 13.3, the impedance of Line $A$ measured by a distance relay, with the normal zero sequence current compensation from its own feeder, is given by:

$$Z_A = nZ_{L1}\left\{1+\frac{\left(I_{B0}/I_{A0}\right)\ M}{2\left(I_{A1}/I_{A0}\right)+K}\right\}$$

...Equation 13.1

where:

$$M = {}^{Z_{M0}}\!/_{Z_{L1}}$$

The true impedance to the fault is $nZ_{L1}$ where $n$ is the per unit fault position measured from $R$ and $Z_{L1}$ is the positive sequence impedance of a single circuit. The 'error' in measurement is determined from the fraction inside the bracket; this varies with the positive and zero sequence currents in circuit $A$ and the zero sequence current in circuit $B$.

These currents are expressed below in terms of the line and source parameters:

$$I_{B0}/I_{A0} =$$

$$\frac{nZ''_{S0}-(1-n)Z'_{S0}}{(2-n)\ Z''_{S0}+(1-n)\ \left(Z'_{S0}+Z_{L0}+Z_{M0}\right)}$$

$$I_{A1}=\frac{(2-n)Z''_{S1}+(1-n)\left(Z'_{S1}+Z_{L1}\right)}{2\left(Z'_{S1}+Z''_{S1}\right)+Z_{L1}}I_1$$

$$I_{A0}=$$

$$\frac{(2-n)Z''_{S0}+(1-n)\left(Z'_{S0}+Z_{L0}+Z_{M0}\right)}{2\left(Z'_{S0}+Z''_{S0}\right)+Z_{L0}+Z_{M0}}I_0$$

*and*

$Z_{M0}$ = zero sequence mutual impedance between the two circuits

NOTE: For earth faults $I_1 = I_0$

All symbols in the above expressions are either self-explanatory from Figure 13.3 or have been introduced in Chapter 11. Using the above formulae, families of reach curves may be constructed, of which Figure 13.4 is typical. In this figure, $n'$ is the effective per unit reach of a relay set to protect 80% of the line. It has been assumed that an infinite busbar is located at each line end, that is, $Z'_{S1}$ and $Z''_{S1}$ are both zero. A family of curves of constant $n'$ has been plotted for variations in the source zero sequence impedances $Z'_{S0}$ and $Z''_{S0}$.

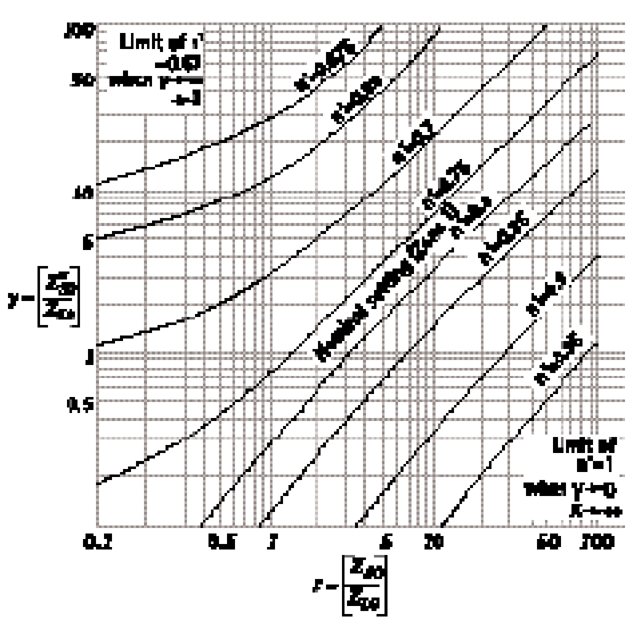

Figure 13.4: Typical reach curves illustrating the effect of mutual coupling

It can be seen from Figure 13.4 that relay $R$ can under-reach or over-reach, according to the relative values of the zero sequence source to line impedance ratios; the extreme effective per unit reaches for the relay are 0.67 and 1. Relay over-reach is not a problem, as the condition being examined is a fault in the protected feeder, for which relay operation is desirable. It can also be seen from Figure 13.4 that relay $R$ is more likely to under-reach. However the relay located at the opposite line end will tend to over-reach. As a result, the Zone 1 characteristic of the relays at both ends of the feeder will overlap for an earth fault anywhere in the feeder – see Section 13.2.3.5 for more details.

Satisfactory protection can be obtained with a transfer trip, under-reach type distance scheme. Further, compensation for the effect of zero sequence mutual impedance is not necessary unless a distance-to-fault facility is provided. Some manufacturers compensate for the effect of the mutual impedance in the distance relay elements, while others may restrict the application of compensation to the distance-to-fault function only. The latter is easy to implement in software for a digital/numerical relay but is impractical in relays using older technologies. Compensation is achieved by injecting a proportion of the zero sequence current flowing in the parallel feeder into the relay. However, some Utilities will not permit this due to the potential hazards associated with feeding a relay protecting one circuit from a CT located in a different circuit.

For the relay to measure the line impedance accurately, the following condition must be met:

$$\frac{V_R}{I_R}=Z_{L1}$$

For a solid phase to earth fault at the theoretical reach of the relay, the voltage and current in the faulty phase at the relaying point are given by:

$$\left.\begin{aligned} V_A &= I_{A1}Z_{L1}+I_{A2}Z_{L2}+I_{A0}Z_{L0}+I_{B0}Z_{M0} \\ I_A &= I_{A1}+I_{A2}+I_{A0} \end{aligned}\right\}$$

...Equation 13.2

The voltage and current fed into the relay are given by:

$$\left.\begin{aligned} V_R &= V_A \\ I_R &= I_A+K_R I_{A0}+K_M I_{B0} \end{aligned}\right\}$$

...Equation 13.3

where:

$K_R$ is the residual compensation factor

$K_M$ is the mutual compensation factor

Thus:

$$K_R=\frac{Z_{L0}-Z_{L1}}{Z_{L1}}$$

$$K_M=\frac{Z_{M0}}{Z_{L1}}$$

### 13.2.2.4 Distance relay behaviour with earth faults on the parallel feeder

Although distance relays with mutual compensation measure the correct distance to the fault, they may not operate correctly if the fault occurs in the adjacent feeder. Davison and Wright [13.1] have shown that, while distance relays without mutual compensation will not over-reach for faults outside the protected feeder, the relays may see faults in the adjacent feeder if mutual compensation is provided. With reference to Figure 13.3, the amount of over-reach is highest when $Z''_{S1}=Z''_{S2}=Z''_{S0}=\infty$. Under these conditions, faults occurring in the first 43% of feeder $A$ will appear to the distance relay in feeder $B$ to be within its Zone 1 reach. The solution is to limit the mutual compensation applied to 150% of the zero sequence compensation.

### 13.2.2.5 Distance relay behaviour with single-circuit operation

If only one of the parallel feeders is in service, the protection in the remaining feeder measures the fault impedance correctly, except when the feeder that is not in service is earthed at both ends. In this case, the zero sequence impedance network is as shown in Figure 13.5.

Humpage and Kandil [13.2] have shown that the apparent impedance presented to the relay under these conditions is given by:

$$Z_R=Z_{L1}-\frac{I_{A0}Z_{M0}^2}{I_R Z_{L0}}$$

...Equation 13.4

where:

$I_R$ is the current fed into the relay

$= I_A + K_R I_{A0}$

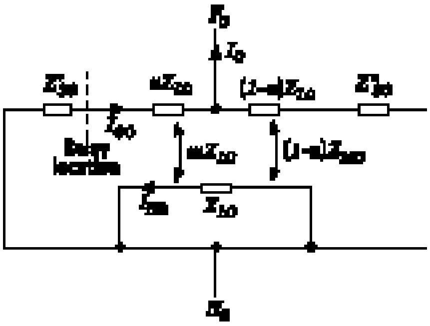

Figure 13.5: Zero sequence impedance network during single circuit operation

The ratio $I_{A0}/I_R$ varies with the system conditions, reaching a maximum when the system is earthed behind the relay with no generation at that end. In this case, the ratio $I_{A0}/I_R$ is equal to $Z_{L1}/Z_{L0}$, and the apparent impedance presented to the relay is:

$$Z_R = Z_{L1}\left(1 - \frac{Z_{M0}^2}{Z_{L0}^2}\right)$$

It is apparent from the above formulae that the relay has a tendency to over-reach. Care should be taken when Zone 1 settings are selected for the distance protection of lines in which this condition may be encountered. In order to overcome this possible over-reaching effect, some Utilities reduce the reach of earth fault relays to around $0.65Z_{L1}$ when lines are taken out of service. However, the probability of having a fault on the first section of the following line while one line is out of service is very small, and many Utilities do not reduce the setting under this condition. It should be noted that the use of mutual compensation would not overcome the over-reaching effect since earthing clamps are normally placed on the line side of the current transformers.

Typical values of zero sequence line impedances for HV lines in the United Kingdom are given in Table 13.1, where the maximum per unit over-reach error $(Z_{M0}/Z_{L0})^2$ is also given. It should be noted that the over-reach values quoted in this table are maxima, and will be found only in rare cases. In most cases, there will be generation at both ends of the feeder and the amount of over-reach will therefore be reduced. In the calculations carried out by Humpage and Kandil, with more realistic conditions, the maximum error found in a 400kV double circuit line was 18.6%.

| | Conductor size | | Zero sequence mutual impedance $Z_{M0}$ | | Zero sequence line impedance $Z_{L0}$ | | Per unit over-reach error $(Z_{M0}/Z_{L0})^2$ |
|---|---|---|---|---|---|---|---|
| Line voltage | (sq.in) | Metric (sq.mm) equivalent | ohms/mile | ohms/km | ohms/mile | ohms/km | |
| 32kV | 0.4 | 258 | 0.3 + j0.81 | 0.19+j0.5 | 0.41+j1.61 | 0.25+j1.0 | 0.264 |
| 275kV | 2 x 0.4 | 516 | 0.18+j0.69 | 0.11+j0.43 | 0.24+j1.3 | 0.15+j0.81 | 0.292 |
| 400kV | 4 x 0.4 | 1032 | 0.135+j0.6 | 0.80+j0.37 | 0.16+j1.18 | 0.1+j0.73 | 0.2666 |

*Table 13.1: Maximum over-reach errors found during single circuit working*

## 13.3 MULTI-ENDED FEEDERS – UNIT PROTECTION SCHEMES

A multi-ended feeder is defined as one having three or more terminals, with either load or generation, or both, at any terminal. Those terminals with load only are usually known as 'taps'.

The simplest multi-terminal feeders are three-ended, and are generally known as tee'd feeders. This is the type most commonly found in practice.

The protection schemes described previously for the protection of two-ended feeders can also be used for multi-ended feeders. However, the problems involved in the application of these schemes to multi-ended feeders are much more complex and require special attention.

The protection schemes that can be used with multi-ended feeders are unit protection and distance schemes. Each uses some form of signalling channel, such as fibre-optic cable, power line carrier or pilot wires. The specific problems that may be met when applying these protections to multi-ended feeders are discussed in the following sections.

### 13.3.1 A.C. Pilot Wire Protection

A.C. pilot wire relays provide a low-cost fast protection; they are insensitive to power swings and, owing to their relative simplicity, their reliability is excellent.

The limitations of pilot wire relays for plain feeder protection also apply. The length of feeder that can be protected is limited by the characteristics of the pilot wires. The protection sees increasing pilot wire resistance as tending to an open circuit and shunt capacitance as an a.c. short circuit across the pilots. The protection will have limiting values for each of these quantities, and when these are exceeded, loss of sensitivity for internal faults and maloperation for external faults may occur. For tee'd feeders, the currents for an external earth fault will not usually be the same. The protection must be linear for any current up to the maximum through-fault value. As a result, the voltage in the pilots during fault conditions cannot be kept to low values, and pilot wires with 250V insulation grade are required.

### 13.3.2 Balanced Voltage Schemes for Tee'd Circuits

In this section two types of older balanced voltage schemes still found in many locations are described.

#### *13.3.2.1 'Translay' balanced voltage protection*

This is a modification of the balanced voltage scheme described in Section 10.7.1. Since it is necessary to maintain linearity in the balancing circuit, though not in the sending element, the voltage reference is derived from separate quadrature transformers, as shown in Figure 13.6. These are auxiliary units with summation windings energized by the main current transformers in series with the upper electromagnets of the sensing elements. The secondary windings of the quadrature current transformers at all ends are interconnected by the pilots in a series circuit that also includes the lower electromagnets of the relays. Secondary windings on the relay elements are not used, but these elements are fitted with bias loops in the usual way.

The plain feeder settings are increased in the tee'd scheme by 50% for one tee and 75% for two.

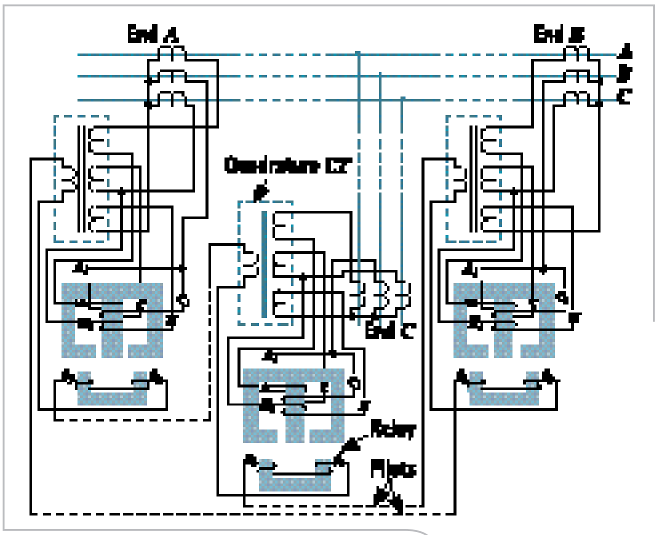

Figure 13.6: Balanced voltage Tee'd feeder scheme

### 13.3.2.2 High - speed protection type DSB7

This type is of higher speed and is shown in Figure 13.7. Summation quadrature transformers are used to provide the analogue quantity, which is balanced in a series loop through a pilot circuit. Separate secondary windings on the quadrature current transformers are connected to full-wave rectifiers, the outputs of which are connected in series in a second pilot loop, so that the electromotive forces summate arithmetically.

The measuring relay is a double-wound moving coil type, one coil being energized from the vectorial summation loop; the other receives bias from the scalar summation in the second loop proportional to the sum of the currents in the several line terminals, the value being adjusted by the inclusion of an appropriate value of resistance. Since the operating and biasing quantities are both derived by summation, the relays at the different terminals all behave alike, either to operate or to restrain as appropriate.

Special features are included to ensure stability, both in the presence of transformer inrush current flowing through the feeder zone and also with a 2-1-1 distribution of fault current caused by a short circuit on the secondary side of a star-delta transformer.

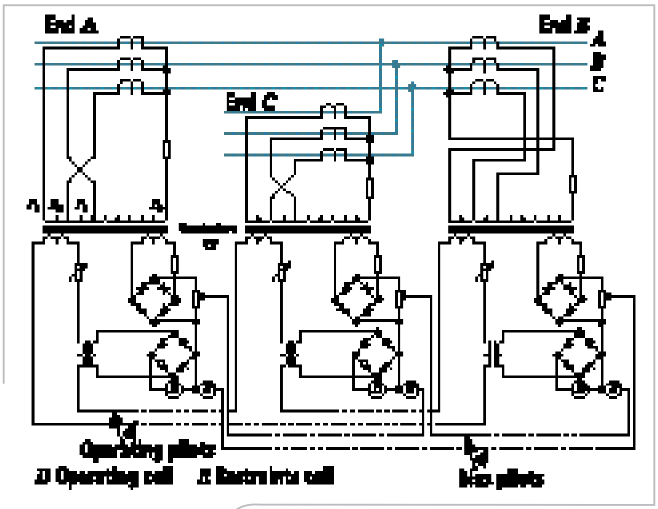

Figure 13.7: Type DSB7 fast tee'd feeder protection

### 13.3.3 Power Line Carrier Phase Comparison Schemes

The operating principle of these protection schemes has already been covered in detail in Section 10.9. It involves comparing the phase angles of signals derived from a combination of the sequence currents at each end of the feeder. When the phase angle difference exceeds a pre-set value, the 'trip angle', a trip signal is sent to the corresponding circuit breakers. In order to prevent incorrect operation for external faults, two different detectors, set at different levels, are used. The low-set detector starts the transmission of carrier signal, while the high-set detector is used to control the trip output. Without this safeguard, the scheme could operate incorrectly for external faults because of operating tolerances of the equipment and the capacitive current of the protected feeder. This condition is worse with multi-terminal feeders, since the currents at the feeder terminals can be very dissimilar for an external fault. In the case of the three-terminal feeder in Figure 13.8, if incorrect operation is to be avoided, it is necessary to make certain that the low-set detector at end $A$ or end $B$ is energized when the current at end $C$ is high enough to operate the high-set detector at that end. As only one low-set starter, at end $A$ or end $B$, needs to be energized for correct operation, the most unfavourable condition will be when currents $I_A$ and $I_B$ are equal. To maintain stability under this condition, the high-set to low-set setting ratio of the fault detectors needs to be twice as large as that required when the scheme is applied to a plain feeder. This results in a loss of sensitivity, which may make the equipment unsuitable if the minimum fault level of the power system is low.

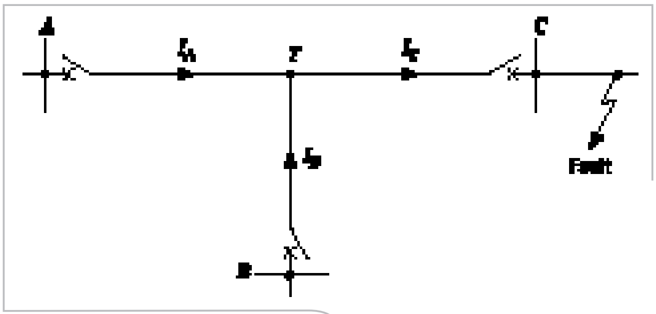

Figure 13.8: External fault conditions

A further unfavourable condition is that illustrated in Figure 13.9. If an internal fault occurs near one of the ends of the feeder (end $B$ in Figure 13.9) and there is little or no generation at end $C$, the current at this end may be flowing outwards. The protection is then prevented from operating, since the fault current distribution is similar to that for an external fault; see Figure 13.8. The fault can be cleared only by the back-up protection and, if high speed of operation is required, an alternative type of primary protection must be used.

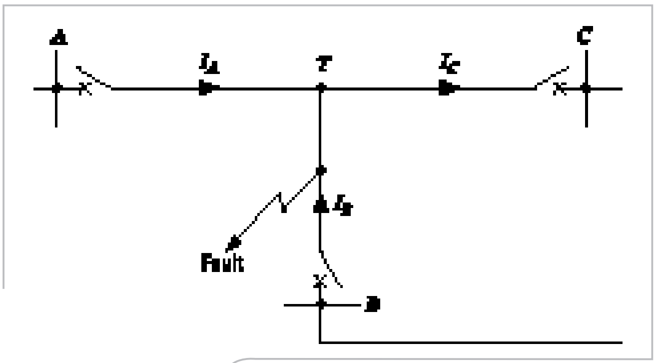

Figure 13.9: Internal fault
with current flowing out at one line end

A point that should also be considered when applying this scheme is the attenuation of carrier signal at the 'tee' junctions. This attenuation is a function of the relative impedances of the branches of the feeder at the carrier frequency, including the impedance of the receiving equipment. When the impedances of the second and third terminals are equal, a power loss of 50% takes place. In other words, the carrier signal sent from terminal $A$ to terminal $B$ is attenuated by $3dB$ by the existence of the third terminal $C$. If the impedances of the two branches corresponding to terminal $B$ to $C$ are not equal, the attenuation may be either greater or less than $3dB$.

### 13.3.4 Differential Relay using Optical Fibre Signalling

Current differential relays can provide unit protection for multi-ended circuits without the restrictions associated with other forms of protection. In Section 8.6.5, the characteristics of optical fibre cables and their use in protection signalling are outlined.

Their use in a three-ended system is shown in Figure 13.10, where the relays at each line end are digital/numerical relays interconnected by optical fibre links so that each can send information to the others. In practice the optical fibre links can be dedicated to the protection system or multiplexed, in which case multiplexing equipment, not shown in Figure 13.10, will be used to terminate the fibres.

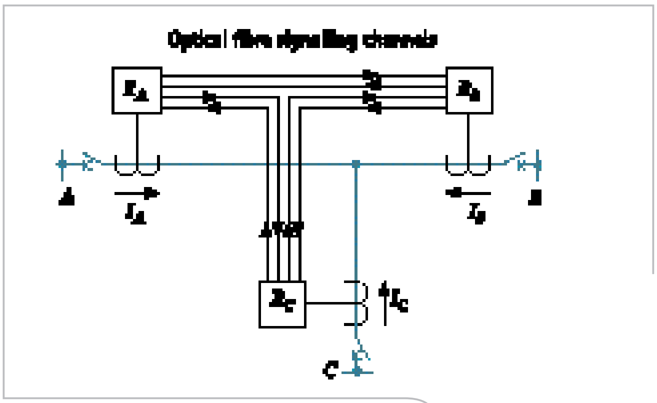

Figure 13.10: Current differential protection
for tee'd feeders using optical fibre signalling

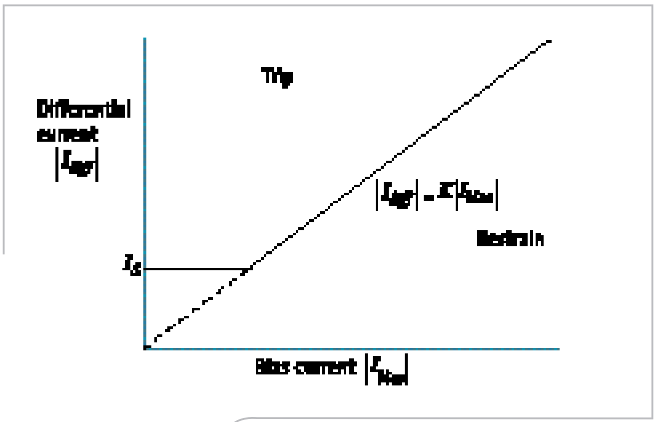

Figure 13.11: Percentage biased
differential protection characteristic

If $I_A$, $I_B$, $I_C$ are the current vector signals at line ends $A$, $B$, $C$, then for a healthy circuit:

$$I_A + I_B + I_C = 0$$

The basic principles of operation of the system are that each relay measures its local three phase currents and sends its values to the other relays. Each relay then calculates, for each phase, a resultant differential current and also a bias current, which is used to restrain the relay in the manner conventional for biased differential unit protection.

The bias feature is necessary in this scheme because it is designed to operate from conventional current transformers that are subject to transient transformation errors.

The two quantities are:

$$|I_{diff}| > |I_A + I_B + I_C|$$

$$|I_{bias}| = \frac{1}{2}\left(|I_A| + |I_B| + |I_C|\right)$$

Figure 13.11 shows the percentage biased differential characteristic used, the tripping criteria being:

$$|I_{diff}| > K|I_{bias}|$$

and

$$|I_{diff}| > I_S$$

where:

$K$ = percentage bias setting

$I_S$ = minimum differential current setting

If the magnitudes of the differential currents indicate that a fault has occurred, the relays trip their local circuit breaker.

The relays also continuously monitor the communication channel performance and carry out self-testing and diagnostic operations. The system measures individual phase currents and so single phase tripping can be used when required. Relays are provided with software to re-configure the protection between two and three terminal lines, so that modification of the system from two terminals to three terminals does not require relay replacement. Further, loss of a single communications link only degrades scheme performance slightly. The relays can recognise this and use alternate communications paths. Only if all communication paths from a relay fail does the scheme have to revert to backup protection.

## 13.4 MULTI-ENDED FEEDERS – DISTANCE RELAYS

Distance protection is widely used at present for tee'd feeder protection. However, its application is not straightforward, requiring careful consideration and systematic checking of all the conditions described later in this section.

Most of the problems found when applying distance protection to tee'd feeders are common to all schemes. A preliminary discussion of these problems will assist in the assessment of the performance of the different types of distance schemes.

### 13.4.1 Apparent Impedance seen by Distance Relays

The impedance seen by the distance relays is affected by the current infeeds in the branches of the feeders. Referring to Figure 13.12, for a fault at the busbars of the substation $B$, the voltage $V_A$ at busbar $A$ is given by:

$$V_A = I_A Z_{LA} + I_B Z_{LB}$$

so the impedance $Z_A$ seen by the distance relay at terminal A is given by:

$$Z_A = \frac{V_A}{I_A} = Z_{LA} + \frac{I_B}{I_A} Z_{LB}$$

or

$$Z_A = Z_{LA} + \frac{I_B}{I_A} Z_{LB}$$

…Equation 13.5

or

$$Z_A = Z_{LA} + Z_{LB} + \frac{I_C}{I_A} Z_{LB}$$

The apparent impedance presented to the relay has been modified by the term $(I_C/I_A)Z_{LB}$. If the pre-fault load is zero, the currents $I_A$ and $I_C$ are in phase and their ratio is a real number. The apparent impedance presented to the relay in this case can be expressed in terms of the source impedances as follows:

$$Z_A = Z_{LA} + Z_{LB} + \frac{(Z_{SB} + Z_{LB})}{(Z_{SC} + Z_{LC})} Z_{LB}$$

The magnitude of the third term in this expression is a function of the total impedances of the branches $A$ and $B$ and can reach a relatively high value when the fault current contribution of branch $C$ is much larger than that of branch $A$. Figure 13.13 illustrates how a distance relay with a mho characteristic located at $A$ with a Zone 2 element set to 120% of the protected feeder $AB$, fails to see a fault at the remote busbar $B$. The 'tee' point $T$ in this example is halfway between substations $A$ and $B$ ($Z_{LA} = Z_{LB}$) and the fault currents $I_A$ and $I_C$ have been assumed to be identical in magnitude and phase angle. With these conditions, the fault appears to the relay to be located at $B'$ instead of at $B$ - i.e. the relay appears to under-reach.

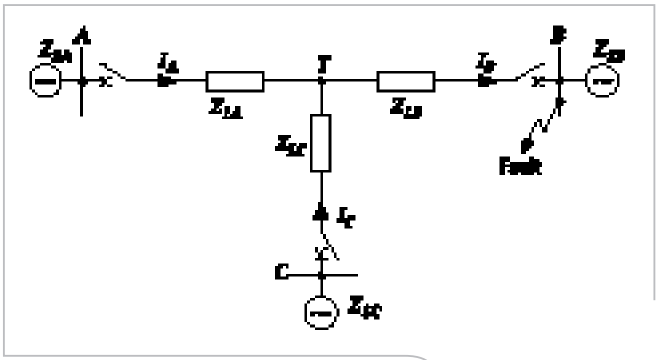

Figure 13.12: Fault at substation B busbars

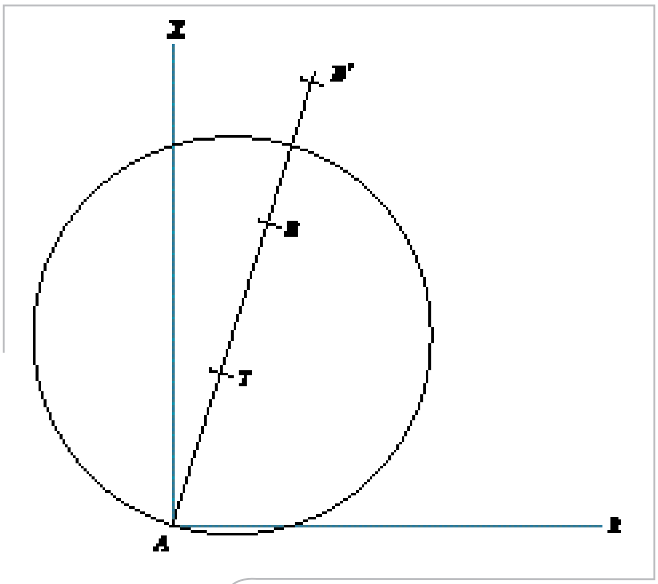

Figure 13.13: Apparent impedance presented to the relay at substation A for a fault at substation B busbars

The under-reaching effect in tee'd feeders can be found for any kind of fault. For the sake of simplicity, the equations and examples mentioned so far have been for balanced faults only. For unbalanced faults, especially those involving earth, the equations become somewhat more complicated, as the ratios of the sequence fault current contributions at terminals $A$ and $C$ may not be the same. An extreme example of this condition is found when the third terminal is a tap with no generation but with the star point of the primary winding of the transformer connected directly to earth, as shown in Figure 13.14. The corresponding sequence networks are illustrated in Figure 13.15.

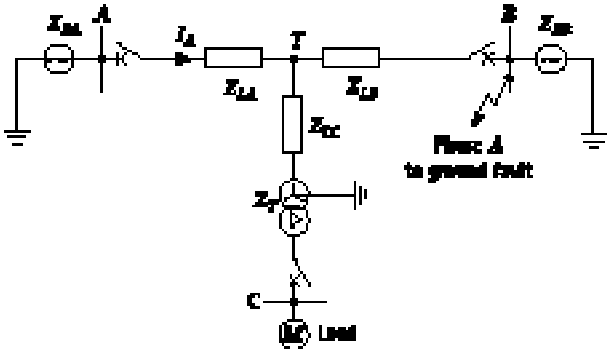

Figure 13.14: Transformer tap with primary winding solidly earthed

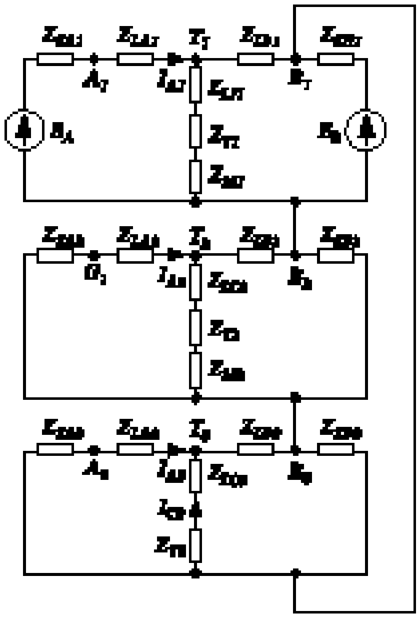

Figure 13.15: Sequence networks for a phase A to ground fault at busbar B in the system shown in Figure 13.14

It can be seen from Figure 13.15 that the presence of the tap has little effect in the positive and negative sequence networks. However, the zero sequence impedance of the branch actually shunts the zero sequence current in branch $A$. As a result, the distance relay located at terminal $A$ tends to under-reach. One solution to the problem is to increase the residual current compensating factor in the distance relay, to compensate for the reduction in zero sequence current. However, the solution has two possible limitations:

i. over-reach will occur when the transformer is not connected, and hence operation for faults outside the protected zone may occur

ii. the inherent possibility of maloperation of the earth fault elements for earth faults behind the relay location is increased

### 13.4.2 Effect of Pre-fault Load

In all the previous discussions it has been assumed that the power transfer between terminals of the feeder immediately before the fault occurred was zero. If this is not the case, the fault currents $I_A$ and $I_C$ in Figure 13.12 may not be in phase, and the factor $I_C/I_A$ in the equation for the impedance seen by the relay at $A$, will be a complex quantity with a positive or a negative phase angle according to whether the current $I_C$ leads or lags the current $I_A$. For the fault condition previously considered in Figures 13.12 and 13.13, the pre-fault load current may displace the impedance seen by the distance relay to points such as $B'_1$ or $B'_2$, shown in Figure 13.16, according to the phase angle and the magnitude of the pre-fault load current. Humpage and Lewis [13.3] have analysed the effect of pre-fault load on the impedances seen by distance relays for typical cases. Their results and conclusions point out some of the limitations of certain relay characteristics and schemes.

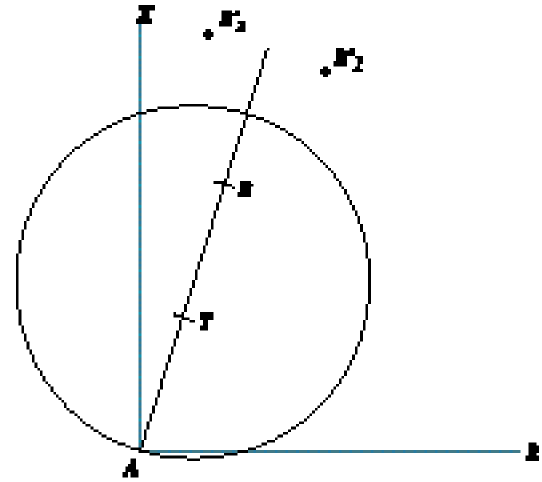

Figure 13.16: effects of the pre-fault load on the apparent impedance presented to the relay

### 13.4.3 Effect of the Fault Current Flowing Outwards at One Terminal

Up to this point it has been assumed that the fault currents at terminals $A$ and $C$ flow into the feeder for a fault at the busbar $B$. Under some conditions, however, the current at one of these terminals may flow outwards instead of inwards. A typical case is illustrated in Figure 13.17; that of a parallel tapped feeder with one of the ends of the parallel circuit open at terminal $A$.

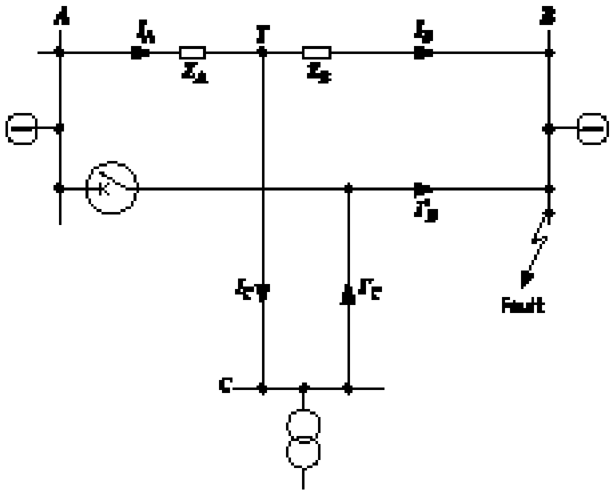

*Figure 13.17: Internal Fault at busbar B with current flowing out at terminal C*

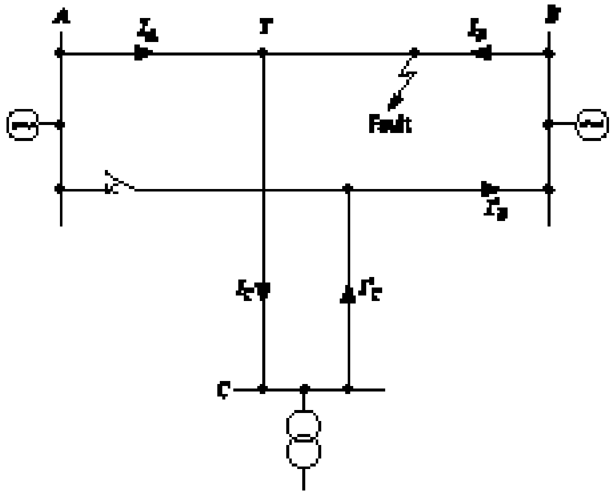

*Figure 13.18: Internal fault near busbar B with current flowing out at terminal C*

As the currents $I_A$ and $I_C$ now have different signs, the factor $I_C/I_A$ becomes negative. Consequently, the distance relay at terminal $A$ sees an impedance smaller than that of the protected feeder, $(Z_A + Z_B)$, and therefore has a tendency to over-reach. In some cases the apparent impedance presented to the relay may be as low as 50% of the impedance of the protected feeder, and even lower if other lines exist between terminals $B$ and $C$.

If the fault is internal to the feeder and close to the busbars $B$, as shown in Figure 13.18, the current at terminal $C$ may still flow outwards. As a result, the fault appears as an external fault to the distance relay at terminal $C$, which fails to operate.

### 13.4.4 Maloperation with Reverse Faults

Earth fault distance relays with a directional characteristic tend to lose their directional properties under reverse unbalanced fault conditions if the current flowing through the relay is high and the relay setting relatively large. These conditions arise principally from earth faults. The relay setting and the reverse fault current are now related, the first being a function of the maximum line length and the second depending mainly on the impedance of the shortest feeder and the fault level at that terminal. For instance, referring to Figure 13.19, the setting of the relay at terminal $A$ will depend on the impedance $(Z_A + Z_B)$ and the fault current infeed $I_C$, for a fault at $B$, while the fault current $I_A$ for a reverse fault may be quite large if the $T$ point is near the terminals $A$ and $C$.

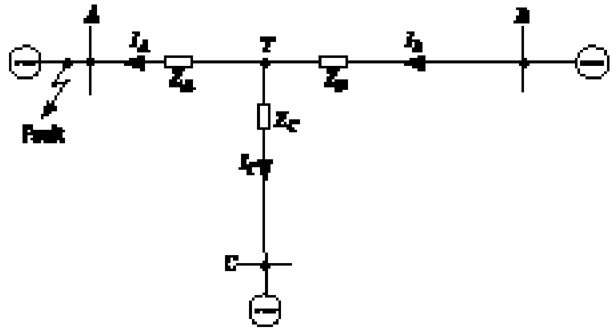

*Figure 13.19: External fault behind he relay at terminal A*

A summary of the main problems met in the application of distance protection to tee'd feeders is given in Table 13.2.

| Case | Description | Relevant figure number |
|---|---|---|
| 1 | Under-reaching effect for internal faults due to current infeed at the T point | 13.12 to 13.15 |
| 2 | Effect of pre-fault load on the impedance seen' by the relay | 13.16 |
| 3 | Over-reaching effect for external faults, due to current flowing outwards at one terminal | 13.17 |
| 4 | Failure to operate for an internal fault, due to current flowing out at one terminal | 13.18 |
| 5 | Incorrect operation for an external fault, due to high current fed from nearest terminal | 13.19 |

*Table 13.2: Main problems met in the application of distance protection to tee'd feeders.*

## 13.5 MULTI-ENDED FEEDERS – APPLICATION OF DISTANCE PROTECTION SCHEMES

The schemes that have been described in Chapter 12 for the protection of plain feeders may also be used for tee'd feeder protection. However, the applications of some of these schemes are much more limited in this case.

Distance schemes can be subdivided into two main groups; transfer trip schemes and blocking schemes. The usual considerations when comparing these schemes are security, that is, no operation for external faults, and dependability, that is, assured operation for internal faults.

In addition, it should be borne in mind that transfer trip schemes require fault current infeed at all the terminals to achieve high-speed protection for any fault in the feeder. This is not the case with blocking schemes. While it is rare to find a plain feeder in high voltage systems where there is current infeed at one end only, it is not difficult to envisage a tee'd feeder with no current infeed at one end, for example when the tee'd feeder is operating as a plain feeder with the circuit breaker at one of the terminals open. Nevertheless, transfer trip schemes are also used for tee'd feeder protection, as they offer some advantages under certain conditions.

### 13.5.1 Transfer Trip Under-Reach Schemes

The main requirement for transfer trip under-reach schemes is that the Zone 1 of the protection, at one end at least, shall see a fault in the feeder. In order to meet this requirement, the Zone 1 characteristics of the relays at different ends must overlap, either the three of them or in pairs. Cases 1, 2 and 3 in Table 13.2 should be checked when the settings for the Zone 1 characteristics are selected. If the conditions mentioned in case 4 are found, direct transfer trip may be used to clear the fault; the alternative is sequentially at end $C$ when the fault current $I_C$ reverses after the circuit breaker at terminal $B$ has opened; see Figure 13.18.

Transfer trip schemes may be applied to feeders that have branches of similar length. If one or two of the branches are very short, and this is often the case in tee'd feeders, it may be difficult or impossible to make the Zone 1 characteristics overlap. Alternative schemes are then required.

Another case for which under-reach schemes may be advantageous is the protection of tapped feeders, mainly when the tap is short and is not near one of the main terminals. Overlap of the Zone 1 characteristics is then easily achieved, and the tap does not require protection applied to the terminal.

### 13.5.2 Transfer Trip Over-Reach Schemes

For correct operation when internal faults occur, the relays at the three ends should see a fault at any point in the feeder. This condition is often difficult to meet, since the impedance seen by the relays for faults at one of the remote ends of the feeder may be too large, as in case 1 in Table 13.2, increasing the possibility of maloperation for reverse faults, case 5 in Table 13.2. In addition, the relay characteristic might encroach on the load impedance.

These considerations, in addition to the signalling channel requirements mentioned later on, make transfer trip over-reach schemes unattractive for multi-ended feeder protection.

### 13.5.3 Blocking Schemes

Blocking schemes are particularly suited to the protection of multi-ended feeders, since high-speed operation can be obtained with no fault current infeed at one or more terminals. The only disadvantage is when there is fault current outfeed from a terminal, as shown in Figure 13.18. This is case 4 in Table 13.2. The protection units at that terminal may see the fault as an external fault and send a blocking signal to the remote terminals. Depending on the scheme logic either relay operation will be blocked, or clearance will be in Zone 2 time.

The setting of the directional unit should be such that no maloperation can occur for faults in the reverse direction; case 5 in Table 13.2.

### 13.5.4 Signalling Channel Considerations

The minimum number of signalling channels required depends on the type of scheme used. With under-reach and blocking schemes, only one channel is required, whereas a permissive over-reach scheme req-uires as many channels as there are feeder ends. The signalling channel equipment at each terminal should include one transmitter and ($N$-1) receivers, where $N$ is the total number of feeder ends. This may not be a problem if fibre-optic cables are used, but could lead to problems otherwise.

If frequency shift channels are used to improve the reliability of the protection schemes, mainly with transfer trip schemes, $N$ additional frequencies are required for the purpose. Problems of signal attenuation and impedance matching should also be carefully considered when power line carrier frequency channels are used.

### 13.5.5 Directional Comparison Blocking Schemes

The principle of operation of these schemes is the same as that of the distance blocking schemes described in the previous section. The main advantage of directional comparison schemes over distance schemes is their greater capability to detect high-resistance earth faults. The reliability of these schemes, in terms of stability for through faults, is lower than that of distance blocking schemes. However, with the increasing reliability of modern signalling channels, directional comparison blocking schemes seem to offer good solutions to the many and difficult problems encountered in the protection of multi-ended feeders. Modern relays implement the required features in different ways – for further information see Chapter 12 and specific relay manuals.

## 13.6 PROTECTION OF SERIES COMPENSATED LINES

Figure 13.20 depicts the basic power transfer equation. It can be seen from this equation that transmitted power is proportional to the system voltage level and load angle whilst being inversely proportional to system impedance. Series compensated lines are used in transmission networks where the required level of transmitted power can not be met, either from a load requirement or system stability requirement. Series compensated transmission lines introduce a series connected capacitor, which has the net result of reducing the overall inductive impedance of the line, hence increasing the prospective, power flow. Typical levels of compensation are 35%, 50% and 70%, where the percentage level dictates the capacitor impedance compared to the transmission line it is associated with.

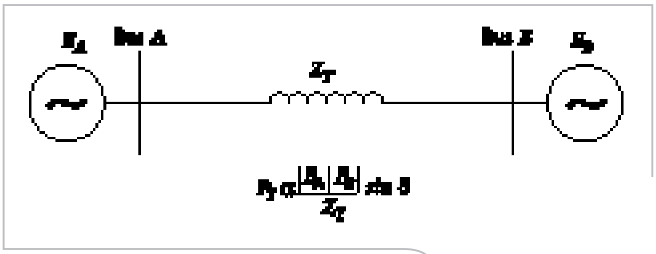

Figure 13.20: Power transfer in a transmission line

The introduction of a capacitive impedance to a network can give rise to several relaying problems. The most common of these is the situation of voltage inversion, which is shown in Figure 13.21. In this case a fault occurs on the protected line. The overall fault impedance is inductive and hence the fault current is inductive (shown lagging the system e.m.f. by 90 degrees in this case). However, the voltage measured by the relay is that across the capacitor and will therefore lag the fault current by 90 degrees.

The net result is that the voltage measured by the relay is in anti-phase to the system e.m.f.. Whilst this view is highly simplistic, it adequately demonstrates potential relay problems, in that any protection reliant upon making a directional decision bases its decision on an inductive system i.e. one where a forward fault is indicated by fault current lagging the measured voltage. A good example of this is a distance relay, which assumes the transmission line is an evenly distributed inductive impedance. Presenting the relay with a capacitive voltage (impedance) can lead the relay to make an incorrect directional decision.

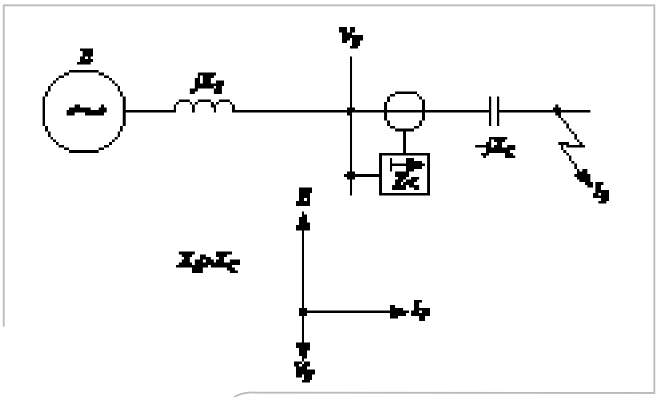

Figure 13.21: Voltage inversion on a transmission line

A second problem is that of current inversion which is demonstrated in Figure 13.22. In this case, the overall fault impedance is taken to be capacitive. The fault current therefore leads the system e.m.f. by 90° whilst the measured fault voltage remains in phase with system e.m.f.. Again this condition can give rise to directional stability problems for a variety of protection devices. Practically, the case of current inversion is difficult to obtain. In order to protect capacitors from high over voltages during fault conditions some form of voltage limiting device (usually in the form of MOV's) is installed to bypass the capacitor at a set current level. In the case of current inversion, the overall fault impedance has to be capacitive and will generally be small. This leads to high levels of fault current, which will trigger the MOV's and bypass the capacitors, hence leaving an inductive fault impedance and preventing the current inversion.

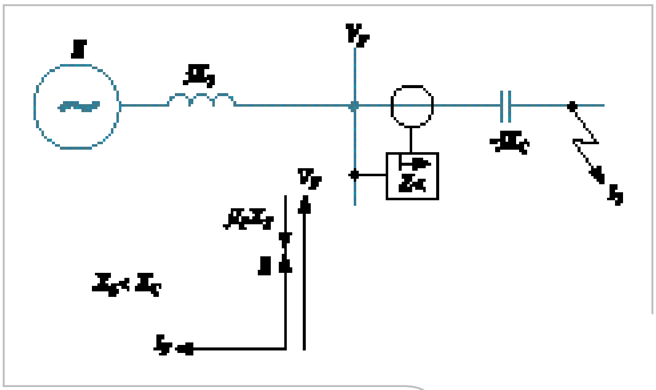

Figure 13.22: Current inversion in a transmission line

In general, the application of protective relays to a series compensated power system needs careful evaluation. The problems associated with the introduction of a series capacitor can be overcome by a variety of relaying techniques so it is important to ensure the suitability of the chosen protection. Each particular application requires careful investigation to determine the most appropriate solution in respect of protection – there are no general guidelines that can be given.

## 13.7 EXAMPLES

In this section, an example calculation illustrating the solution to a problem mentioned in this Chapter is given.

### 13.7.1 Distance Relay applied to Parallel Circuits

The system diagram shown in Figure 13.23 indicates a simple 110kV network supplied from a 220kV grid through two auto-transformers. The following example shows the calculations necessary to check the suitability of three zone distance protection to the two parallel feeders interconnecting substations *A* and *B*, Line 1 being selected for this purpose. All relevant data for this exercise are given in the diagram. The MiCOM P441 relay with quadrilateral characteristics is used to provide the relay data for the example. Relay quantities used in the example are listed in Table 13.3, and calculations are carried out in terms of actual system impedances in ohms, rather than CT secondary quantities. This simplifies the calculations, and enables the example to be simplified by excluding considerations of CT ratios. Most modern distance relays permit settings to be specified in system quantities rather than CT secondary quantities, but older relays may require the system quantities to be converted to impedances as seen by the relay.

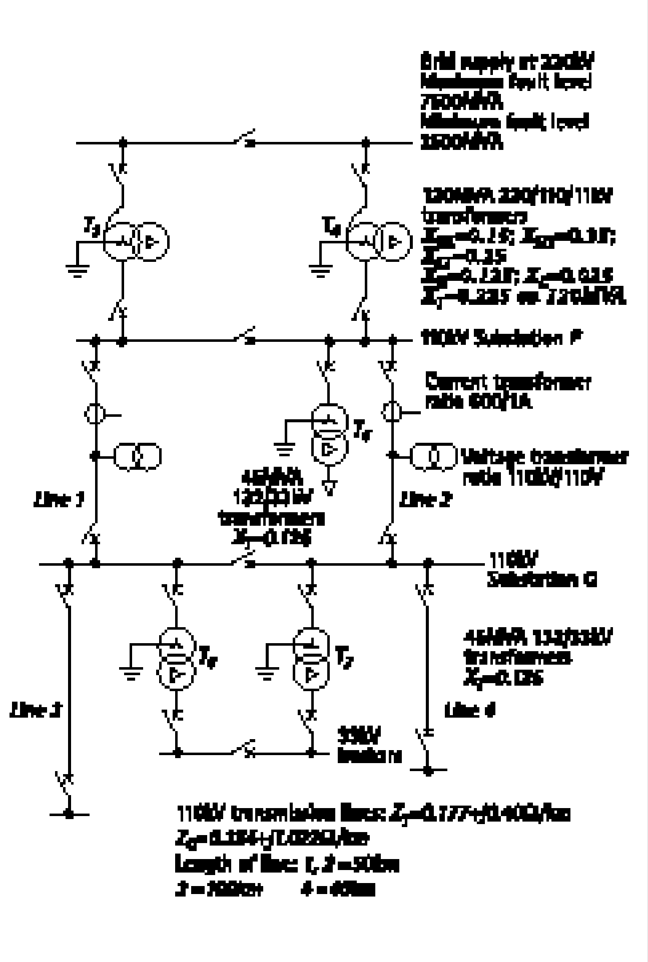

Figure 13.23: Example network for distance relay setting calculation

| Relay Parameter | Parameter Description | Parameter Value | Units |
|---|---|---|---|
| $Z_{L1}$ (mag) | Line positive sequence impedance (magnitude) | 21.95 | Ω |
| $Z_{L1}$ (ang) | Line positive sequence impedance (phase angle) | 66.236 | deg |
| $Z_{L0}$ (mag) | Line zero sequence impedance (magnitude) | 54.1 | Ω |
| $Z_{L0}$ (ang) | Line zero sequence impedance (phase angle) | 70.895 | deg |
| $K_{Z0}$ (mag) | Default residual compensation factor (magnitude) | 0.49 | - |
| $K_{Z0}$ (ang) | Default residual compensation factor (phase angle) | 7.8 | deg |
| $Z_1$ (mag) | Zone 1 reach impedance setting (magnitude) | 17.56 | Ω |
| $Z_1$ (ang) | Zone 1 reach impedance setting (phase angle) | 66.3 | deg |
| $Z_2$ (mag) | Zone 2 reach impedance setting (magnitude) | 30.73 | Ω |
| $Z_2$ (ang) | Zone 2 reach impedance setting (phase angle) | 66.3 | deg |
| $Z_3$ (mag) | Zone 3 reach impedance setting (magnitude) | 131.8 | Ω |
| $Z_3$ (ang) | Zone 3 reach impedance setting (phase angle) | 66.3 | deg |
| $R_{1ph}$ | Phase fault resistive reach value - Zone 1 | 84.8 | Ω |
| $R_{2ph}$ | Phase fault resistive reach value - Zone 2 | 84.8 | Ω |
| $R_{3ph}$ | Phase fault resistive reach value - Zone 3 | 84.8 | Ω |
| $K_{Z1}$ (mag) | Zone 1 residual compensation factor (magnitude) | 0.426 | - |
| $K_{Z1}$ (ang) | Zone 1 residual compensation factor (phase angle) | 9.2 | deg |
| $K_{Z2}$ (mag) | Zone 2 residual compensation factor (magnitude) | not used | - |
| $K_{Z2}$ (ang) | Zone 2 residual compensation factor (phase angle) | not used | deg |
| $T_{Z1}$ | Time delay - Zone 1 | 0 | s |
| $T_{Z2}$ | Time delay - Zone 2 | 0.25 | s |
| $T_{Z3}$ | Time delay - Zone 3 | 0.45 | s |
| $R_{1G}$ | Ground fault resistive reach value - Zone 1 | 84.8 | Ω |
| $R_{2G}$ | Ground fault resistive reach value - Zone 2 | 84.8 | Ω |
| $R_{3G}$ | Ground fault resistive reach value - Zone 3 | 84.8 | Ω |

Table 13.3: Distance relay settings

#### 13.7.1.1 Residual compensation

The relays used are calibrated in terms of the positive sequence impedance of the protected line. Since the earth fault impedance of Line 1 is different from the positive sequence impedance, the impedance seen by the relay in the case of a fault involving earth will be different to that seen for a phase fault. Hence, the reach of the earth fault elements of the relay needs to be different.

For the relay used, this adjustment is provided by the residual (or neutral) compensation factor $K_{zo}$, set equal to:

$$|K_{ZO}| = \left| \frac{(Z_o - Z_1)}{3Z_1} \right|$$

$$\angle K_{ZO} = \angle \frac{(Z_o - Z_1)}{3Z_1}$$

For Lines 1 and 2,

$$Z_{L1} = 0.177 + j0.402\Omega$$

$$(0.439\angle 66.236^o\,\Omega)$$

$$Z_{LO} = 0.354 + j1.022\Omega$$

$$(1.082\angle 70.895^o\,\Omega)$$

Hence,

$$|K_{ZO}| = 0.490$$

$$\angle K_{ZO} = 7.8^o$$

### 13.7.1.2 Zone impedance reach settings – phase faults

Firstly, the impedance reaches for the three relay zones are calculated.

### 13.7.1.3 Zone 1 reach

Zone 1 impedance is set to 80% of the impedance of the protected line. Hence,

$$Z_1 = 0.8 \times 50 \times \left(0.439\angle 66.236^o\right)\Omega$$

$$= 0.8 \times 21.95\angle 66.236^o\,\Omega$$

$$= 17.56\angle 66.236^o\,\Omega$$

Use a value of $17.56\angle 66.3^o\,\Omega$

### 13.7.1.4 Zone 2 reach

Zone 2 impedance reach is set to cover the maximum of:

(i) 120% of Line 1 length

(ii) Line 1 + 50% of shortest line from Substation $B$ i.e. 50% of Line 4

From the line impedances given,

(i) $1.2 \times 21.95\ \angle\ 66.236^o = 26.34\angle 66.236^o\,\Omega$

(ii) $21.95\angle 66.236^o +$

$0.5 \times 40 \times 0.439\angle 66.236^o\,\Omega$

It is clear that condition (ii) governs the setting, and therefore the initial Zone 2 reach setting is:

$$Z_2 = 30.73\angle 66.3^o\,\Omega$$

The effect of parallel Line 2 is to make relay 1 underreach for faults on adjacent line sections, as discussed in Section 11.9.3. This is not a problem for the phase fault elements because Line 1 will always be protected.

### 13.7.1.5 Zone 3 reach

The function of Zone 3 is to provide backup protection for uncleared faults in adjacent line sections. The criterion used is that the relay should be set to cover 120% of the impedance between the relay location and the end of the longest adjacent line, taking account of any possible fault infeed from other circuits or parallel paths. In this case, faults in Line 3 will result in the relay under-reaching due to the parallel Lines 1 and 2, so the impedance of Line 3 should be doubled to take this effect into account. Therefore,

$$Z_3 = 1.2 \times \begin{pmatrix} 21.95\angle 66.3^o \\ +100 \times 2 \times 0.439\angle 66.3^o \end{pmatrix}\Omega$$

$$= 131.8\angle 66.3^o\,\Omega$$

### 13.7.1.6 Zone Time Delay Settings

Proper co-ordination of the distance relay settings with those of other relays is required. Independent timers are available for the three zones to ensure this.

For Zone 1, instantaneous tripping is normal. A time delay is used only in cases where large d.c. offsets occur and old circuit breakers, incapable of breaking the instantaneous d.c. component, are involved.

The Zone 2 element has to grade with the relays protecting Lines 3 and 4 since the Zone 2 element covers part of these lines. Assuming that Lines 3/4 have distance, unit or instantaneous high-set overcurrent protection applied, the time delay required is that to cover the total clearance time of the downstream relays. To this must be added the reset time for the Zone 2 elements following clearance of a fault on an adjacent line, and a suitable safety margin. A typical time delay is 250ms, and the normal range is 200-300ms.

The considerations for the Zone 3 element are the same as for the Zone 2 element, except that the downstream fault clearance time is that for the Zone 2 element of a distance relay or IDMT overcurrent protection. Assuming distance relays are used, a typical time is 450ms. In summary:

$T_{Z1} = 0ms$ (instantaneous)

$T_{Z2} = 250ms$

$T_{Z3} = 450ms$

### 13.7.1.7 Phase Fault Resistive Reach Settings

With the use of a quadrilateral characteristic, the resistive reach settings for each zone can be set independently of the impedance reach settings. The resistive reach setting represents the maximum amount of additional fault resistance (in excess of the line impedance) for which a zone will trip, regardless of the fault within the zone.

Two constraints are imposed upon the settings, as follows:

(i) it must be greater than the maximum expected phase-phase fault resistance (principally that of the fault arc)

(ii) it must be less than the apparent resistance measured due to the heaviest load on the line

The minimum fault current at Substation $B$ is of the order of 1.5kA, leading to a typical arc resistance $R_{arc}$ using the van Warrington formula (equation 11.6) of 9Ω. Using the current transformer ratio on Line 1 as a guide to the maximum expected load current, the minimum load impedance $Z_{lmin}$ will be 106Ω. Typically, the resistive reaches will be set to avoid the minimum load impedance by a 20% margin for the phase elements, leading to a maximum resistive reach setting of 84.8Ω.

Therefore, the resistive reach setting lies between 9Ω and 84.8Ω. While each zone can have its own resistive reach setting, for this simple example, all of the resistive reach settings can be set equal (depending on the particular distance protection scheme used and the need to include Power Swing Blocking, this need not always be the case).

Suitable settings are chosen to be 80% of the load resistance:

$$R_{3\,ph} = 84.8\Omega$$

$$R_{2\,ph} = 84.8\Omega$$

$$R_{1\,ph} = 84.8\Omega$$

### 13.7.1.8 Earth Fault Reach Settings

By default, the residual compensation factor as calculated in section 13.7.1.1 is used to adjust the phase fault reach setting in the case of earth faults, and is applied to all zones. However, it is also possible to apply this compensation to zones individually. Two cases in particular require consideration, and are covered in this example.

### 13.7.1.9 Zone 1 earth fault reach

Where distance protection is applied to parallel lines (as in this example), the Zone 1 earth fault elements may sometimes over-reach and therefore operate when one line is out of service and earthed at both ends

The solution is to reduce the earth fault reach of the Zone 1 element to typically 80% of the default setting. Hence:

$$\begin{aligned} K_{Z1} &= 0.8 \times K_{Z0} \\ &= 0.8 \times 0.532 \\ &= 0.426 \end{aligned}$$

In practice, the setting is selected by using an alternative setting group, selected when the parallel line is out of service and earthed.

### 13.7.1.10 Zone 2 earth fault reach

With parallel circuits, the Zone 2 element will tend to under-reach due to the zero sequence mutual coupling between the lines.

Maloperation may occur, particularly for earth faults occurring on the remote busbar. The effect can be countered by increasing the Zone 2 earth fault reach setting, but first it is necessary to calculate the amount of under-reach that occurs.

$$Underreach = Z_{adj} \times \frac{I_{fltp}}{I_{flt}}$$

where:

$Z_{adj}$ = impedance of adjacent line covered by Zone 2

$I_{fltp}$ = fault current in parallel line

$I_{flt}$ = total fault current

since the two parallel lines are identical, and hence, for Lines 1 and 2,

$$\begin{aligned} Under\text{-}reach &= 8.78\angle 66.3^{o} \times 0.5 \\ &= 4.39\angle 66.3^{o}\ \Omega \end{aligned}$$

$$\%\ Under\text{-}reach = \frac{Under\text{-}reach}{Reach\ of\ protected\ zone}$$

and hence

$$\%\ Under\text{-}reach = 14.3\%$$

This amount of under-reach is not significant and no adjustment need be made. If adjustment is required, this can be achieved by using the $K_{Z2}$ relay setting, increasing it over the $K_{Z0}$ setting by the percentage under-reach. When this is done, care must also be taken that the percentage over-reach during single circuit operation is not excessive – if it is then use can be made of the alternative setting groups provided in most modern distance relays to change the relay settings according to the number of circuits in operation.

### 13.7.1 11 Ground fault resistive reach settings

The same settings can be used as for the phase fault resistive reaches. Hence,

$R_{3G} = 84.8\Omega$
$R_{2G} = 84.8\Omega$
$R_{1G} = 84.8\Omega$

This completes the setting of the relay. Table 13.3 also shows the settings calculated.

## 13.8 REFERENCES

13.1 *Some factors affecting the accuracy of distance type protective equipment under earth fault conditions.* Davison, E.B. and Wright, A. Proc. IEE Vol. 110, No. 9, Sept. 1963, pp. 1678-1688.

13.2 *Distance protection performance under conditions of single-circuit working in double-circuit transmission lines.* Humpage, W.D. and Kandil, M.S. Proc. IEE. Vol. 117. No. 4, April 1970, pp. 766-770.

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