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# APPLICATION GUIDE ON PROTECTION OF COMPLEX TRANSMISSION NETWORK CONFIGURATIONS

Working Group 04
of
Study Committee 34 (Protection)

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## Acknowledgement

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## Contents

# 1 Scope and Object

This Guide is primarily aimed at the application engineer who has a basic protection knowledge but needs expert assistance to plan and operate the protection of more complex transmission systems. This publication may however, also be of interest for experienced engineers as it contains recent information collected through analysis of the responses to a world-wide survey questionnaire issued in 1989.

The following topics are covered:

- Review of the fundamental problems associated with the protection of multicircuit lines (double lines) multi-terminal and tapped lines, as well as series compensated lines.
- Investigation of basic protection schemes covering the above mentioned applications and proposals for adequate solutions to the protection problems
- Survey of the common practices

# 2 Introduction

The protection of complex transmission networks requires, as a rule, an individual consideration of each application case. A standard situation does normally not exist.

Conventional off-the-shelf protection schemes, like distance relays must at least be specially set, need supplementary equipment or may even need specially modified characteristics.

The simple linear connection between fault impedance and distance-to-fault can normally not be assumed due to

- intermediate in- or outfeeds (multi-terminal lines)
- zero-sequence mutual coupling (parallel lines)
- discontinuities (series compensated lines).

This results in a varying zone reach and causes consequently problems to achieve selective zone setting for a dependable and secure fault clearance.

Directional relays may be adversely affected by possible voltage or current inversions (series compensated lines) or may sense a false fault direction due to induced voltages (parallel lines) and outfeed conditions (multi-terminal lines).

Partly sophisticated protection schemes in combination with telecommunication must therefore be used to solve these problems.

As a rule, the protection setting has to be based on a short-circuit study that considers the named influencing factors. In most cases, however, the network can be reduced to the line configurations to be protected (e.g. three-terminal- or parallel line) with representative infeeds at each terminal. Thus, extensive computer studies are only needed in the exceptional case.

To use this guide, the basics of fault analysis and protective relaying are assumed as known. The symmetrical component analysis is used to study unsymmetrical fault types.

The bibliography provided at the end of this documentation contains in the first general part relevant literature. Manufacturers' relay application descriptions can be taken as a further source for information.

For the special subject of protection using telecommunication the relevant CIGRE Publications [13,14] provide an excellent introduction.

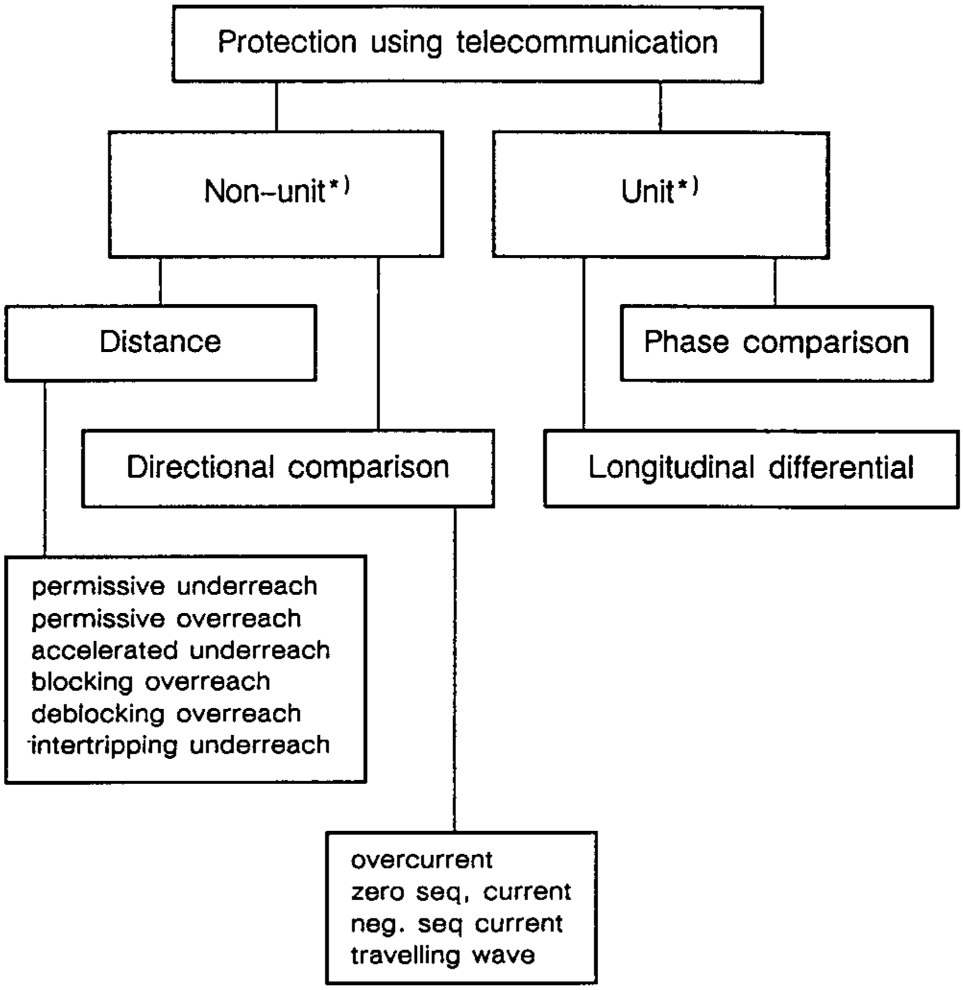
# 3 Terminology

This document uses IEC recommended graphical and letter symbols [6,7].

The protection terminology is adapted to the International Electrotechnical Vocabulary, chapter 448: Power System Protection [8].

Telecommunication is a widely used means to upgrade the protection for complex transmission systems.

Figure 3.1 shows the currently applied schemes.




note: sometimes permissive overreach distance protection is called directional comparison
Zero sequence current protection is also called residual current protection
*)The terms "Unit" and "Non-Unit" are explained on page 13.

**Fig. 3.1: The most common protections using telecommunication**

Readers not familiar with these terms and their meaning are referred to the CIGRE Publication:
Protection Systems Using Telecommunication
CIGRE WG34/35-05 October 1987

The following abbreviations are introduced for the frequently occurring protection schemes:

DPO = distance protection only, second zone tripping for near-line-end faults accepted
DPZS = distance protection with autoreclosure-controlled zone switching
(normally the overreaching zone is switched back to underreaching during the AR dead-time)
IUDP = intertripping underreach distance protection
PUDP = permissive underreach distance protection
PODP = permissive overreach distance protection
AUDP = accelerated underreach distance protection
BODP = blocking overreach distance protection
DBODP = deblocking overreach distance protection
CPCP = composite-current phase-comparison protection
SPCP = phase-segregated phase-comparison protection
PWDP = pilot wire differential protection
FODP = fiber-optic differential protection
MWDP = micro-wave differential protection
TWMP = travelling wave protection with microwave channel
TWCP = travelling wave protection with carrier channel
DEPZ = directional comparison earth fault protection, based on the zero-sequence components
DEPN = directional comparison earth fault protection, based on the negative-sequence components
DEP = directional earth-fault protection, time delayed without telecommunication
NDEP = non-directional earth-fault protection, time delayed without telecommunication

The following further abbreviations are used in this documentation:

AR = Autoreclosure
CB = Circuit breaker
CT = Current transformer
EHV = Extra high voltage (300 - 999 kV)
FO = Fibre optic
FSK = Frequency shift keying
GP = Gas pressure relay
HV = High voltage (100 - 299 kV)
IT = Intertripping
MCTL = Multi-circuit transmission line
MOV = Metal-oxide varistor
MTL = Multi-terminal line
MW = Microwave
OHL = Overhead line
O/C = Over-current
PCM = Pulse-code modulation
PCP = Phase comparison protection
PLC = Power line carrier
S/R = Sender/Receiver
SSR = Subsynchronous resonance
TL = Tapped line
TLB = Tapped line with backfeed
VT = Voltage transformer

Related to the protection of complex transmission networks the following additional terms are often used:

**Compensation degree (of a series-compensated line)**

Percentage of the equivalent series-capacitor reactance on a line in relation to the line reactance: $k = X_C / X_L$.

**Composite current protection**

A single-system protection operating on basis of a mixed-current measuring quantity composed of the weighted current sum of a three-phase system ($I_M = k_1 \cdot I_a + k_2 \cdot I_b + k_3 \cdot I_c$).

**Composite line**

Power transmission line consisting of electrically different series connected components, e.g. a series connection of cable- and OHL-sections.

**Conventional airgap**

An airgap which will flash when the voltage over the capacitor becomes higher than the capacitor is designed to stand.

**Cross-country fault**

Simultaneous flash-over to earth of two different phases in different line sections.

**Current reversal**

Reversal of the fault-current on a healthy line due to non-simultaneous fault clearing e.g. when the circuit breakers switch-off a fault on a parallel line at sequential instants.

**Double fault**

Simultaneous faults on two circuits of a multi-circuit line at the same location. E.g. a phase-to-earth fault on each circuit at the same tower of a double-circuit line.

**Evolving fault**

A fault developing to involve different phases/earth during the fault clearing time.

**Flash-over fault**

Flash-over between phase-conductors of two different circuits of a multi-circuit line.

**Intercircuit fault**

Fault between the circuits of a multi-circuit line with or without involving earth (same voltage level).

**Intersystem fault**

Fault between circuits of a multi-circuit line where the circuits belong to different power systems (voltage levels).

**Line-end series-capacitor**

Series capacitor placed at the end of a power line.

**Line tap**

A connection to a line with equipment that does not feed energy into a fault on the line in sufficient magnitude to require consideration in the relay plan.

**Line terminal**

A connection to a line with equipment that can feed energy into a fault on the line in sufficient magnitude to require consideration in the relay plan and which has means for automatic disconnection.

**Mid-line series-capacitor**

Series capacitor not placed at the end of a power line.

**Multi-circuit line**

In the protection sense of this paper the term defines a configuration of power lines running so closely parallel that they can influence each other and adversely affect the protection performance.

**Multi-terminal line**

Line configuration with three or more line terminals with substantial generation behind each.

**Mutual Coupling**

Inductive or capacitive interaction of parallel power systems.
In the protection sense this term defines normally the inductive coupling of the zero-sequence systems of parallel lines.

**Negative reactance**

When the reactance from the relay location to the series-capacitor is less than the equivalent negative reactance of the capacitor, the situation is called negative reactance. (See also: voltage inversion and negative fault voltage)

**Negative fault current**

When the negative reactance of the series-capacitor ($X_C = -1/_{\omega C}$) is larger than the sum of the source- and line fault-reactance, then the total fault loop impedance becomes negative and the fault current will be inverted compared to the normal inductive case, i.e. the fault current will have a leading phase angle against the EMF-voltage. This inverted current is then called "negative fault current".

**Negative fault voltage**

If the short-circuit impedance becomes negative (see "negative reactance"), then the short-circuit voltage will be inverted compared to the normal inductive case and will then be called "negative fault voltage".

**Outfeed**

Condition at a line terminal of a multi-terminal line where the shortcircuit power flows out of the line with an internal fault.

**Phase segregated protection**

A protection that operates with separate measuring systems per phase.

**Resistor airgap**

In this paper this term is an abbreviation for a non-linear resistor made of metal-oxide protecting the series-capacitor. Normally a conventional airgap is additionally installed and considered as a back-up to the metal-oxide resistor.

**Secondary (consequential) fault**

Fault caused directly or indirectly by another fault.

**Series-capacitor bank**

Capacitor elements connected together in series and parallel to form a large bank with high capacitance and high rated current.

**Series-capacitor segment**

A series-capacitor can be divided into two or more segments.

**Series-compensated line**

A power transmission line that has series-connected capacitors for reactive power compensation. The lumped negative short-circuit reactance of the series-capacitor can cause voltage and even current inversions and can adversely affect protection systems.

**Tapped line**

A line having one or more terminals with substantial generation behind them and taps feeding only loads. The taps have not sufficient current feed-back to operate relays.

**Teed-line**

Three terminal line.

**Transformer feeder**

A line connected to a power transformer without intermediate circuit breaker, i.e. the remote line end circuit breaker must be tripped in case of a transformer fault.

**Unit protection**

A protection whose operation and section selectivity are dependent on the comparison of electrical quantities at each end of the protected section.

**Non-unit protection**

A protection whose operation and section selectivity are solely dependent on the measurement of electrical quantities at one end of the protected section.

**Voltage inversion**

On series-compensated lines, the reactance from the relay-location to the fault point may become negative (see "negative reactance"). In this case the short-circuit voltage will assume a lagging phase-angle against the short-circuit current, i.e. it will be inverted compared to the normal case of an inductive short-circuit reactance.

**Weak-infeed**

Condition at a line terminal where the infeed current is not strong enough to operate (start) the protection at this terminal for an internal fault.

# 4 Protection of multi-circuit transmission lines

## 4.1 Introduction

The term multi-circuit transmission line (MCTL) is used when two or more three-phase transmission circuits are arranged on the same tower or follow the same right-of-way on adjacent towers. The circuits may be of the same or of different voltage level(s).

Due to magnetic induction the circuits are mutually coupled. This phenomenon has to be considered for the fault calculation and the protection design.

### 4.1.1 Application range

Environmental and cost considerations force the utilities to use the granted right-of-ways as effectively as possible. Especially in heavily populated areas multi-circuit lines are therefore widely used with up to six systems on one tower.

This locally close arrangement of power lines, especially on common towers, however, always bears the risk that simultaneous or consequential faults can occur on parallel systems due to back-flashover, falling-down of broken conductors or conductor gallopping. The statistics of faults involving more than one parallel circuit vary considerable between utilities and local conditions. Values of 10 to 20% seem to be normal.

Faults between circuits of different voltage level are seldom (about one case in 10 years per utility according to the replies to the 1989 CIGRE-questionnaire), but cause dangerous voltage and current strain in the lower voltage system [4.24].

The lay-out of the protection to enable selective fault clearance with these multiple faults is always a challenging task for the protection engineer.

Especially for the relatively often occurring multiple earth faults on parallel lines, phase selective tripping and single-pole autoreclosure at each circuit should be ensured to avoid the outage of both lines at the same time.

In the classical case a double circuit or parallel line exists where two equal circuits are mounted on the same towers and connect the same substations.

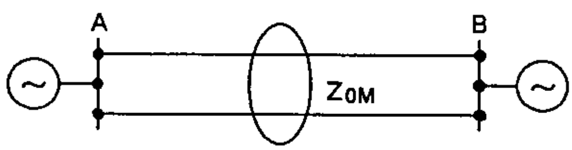



**Fig. 4.1: Parallel line, same bus at both ends**

From the protection point of view the simplest case is given when both systems are connected to the same infeed sources (busbars) in each station. The proximity of the parallel line terminals makes it possible to apply compensation methods against mutual coupling, if necessary.

Often the case occurs where the lines are conducted only partly parallel and end at separate substations at the remote end.

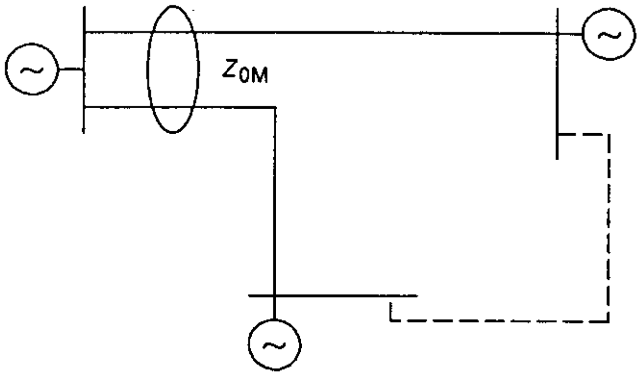



**Fig. 4.2: Parallel line with one common bus only**

This allows the application of compensation only in one substation.

The most unfavorable condition is given when lines run parallel but end at different substations at both line ends.

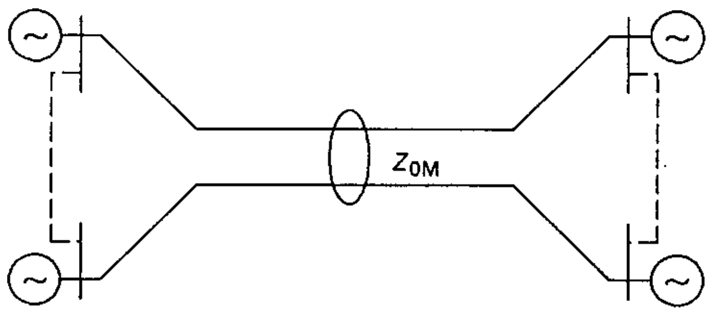



**Fig. 4.3: Parallel line, separate buses at both ends**

No compensation of the mutual coupling effects is possible in this case.

Complex fault conditions may occur when the parallel lines belong to different power systems possibly also of different voltage levels. Complicated short circuit voltage- and current distributions result from the mutual coupling and double faults involving both circuits.

### 4.1.2 Mutual coupling effect

**Fundamentals:**

The mutual coupling is based on the known induction law: The current sets-up a magnetic field around its conductor. If this field cuts parallel conductors, it induces longitudinal voltages along them.

The induced voltage is:

(4.1) $V_b = Z_M \cdot I_a$

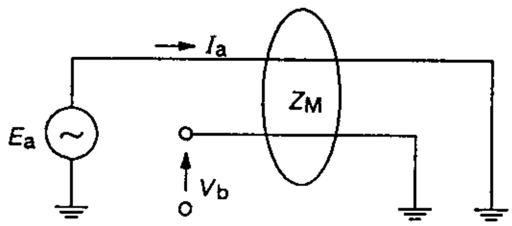



**Fig. 4.4: Mutual coupling**

The mutual impedance $z_M'$ of two conductors with common earth return can be taken from relevant textbooks [11]:

(4.2) $$z_M' = \frac{\pi \cdot \mu_o}{4} \cdot f + j\mu_o \cdot f \cdot ln \frac{\delta}{D_{ab}} \quad \Omega/km$$

$\mu_o = 4\pi \cdot 10^{-4} \quad \Omega \cdot sec/km$

f = Frequency in Hz

$\delta = 658 \sqrt{\frac{\rho}{f}}$ = penetration depth of the earth-current in meter

$\rho$ = earth resistivity in $\Omega \cdot m$

$D_{ab}$ = mean distance in meter between conductors a and b.

With a typical earth resistivity of $\rho = 100\Omega m$ and a system frequency of 50Hz we get

$$z_M' = 0.05 + j\ 0.1445 \log \frac{930}{D_{ab\,[m]}} \quad \Omega/km$$

For an assumed conductor distance of 20 meters the coupling impedance can be calculated as:

$z_M' = 0.05 + j\ 0.24 \quad \Omega\ /\ km$

We can now estimate the induced voltage on parallel conductors $U_b = Z_M \cdot I_a$.

For the case of 20 meter conductor distance we get about 250 Volts on conductor b per 1000A and km, i.e. for a length of 100km and 2000A short-circuit current 50kV would result.

We notice that the induced voltage decreases in a logarithmic dependance of the conductor distance. But, for our last example we would still get 20kV at a distance of 200 meter, i.e. distances of up to some 100m have a measurable influence.

**Mutual induction on three-phase transmission lines**

In this case coupling exists between all conductors of a multi-circuit line.

Under load condition and faults without earth the current-sum of one line is zero. If the distances of the conductors between the two three-phase circuits are assumed as equal then the induction of the different conductors cancel each other and the mutual coupling is theoretically zero.

With the real arrangement of the conductors at the tower, some unsymmetry is unavoidable even when the lines are transposed [11,4.4].

Practically, the mutual coupling in the positive and negative sequence system is relatively weak and can be neglected for normal protection considerations. The mutual impedance is in this case usually below 5 percent of the related self-impedance for untransposed lines and lower than 3 percent for transposed lines [4.4].

The zero sequence currents are equal and in phase in all three conductors of the three-phase line, i.e. the effects of the conductors add to a maximum. In this case the three phase-conductors can be replaced by a representative single conductor for each parallel line and the mutual coupling between lines and their earth wires is then reduced to a single-phase problem [11].

The zero-sequence mutual impedance is defined and can be measured as follows:

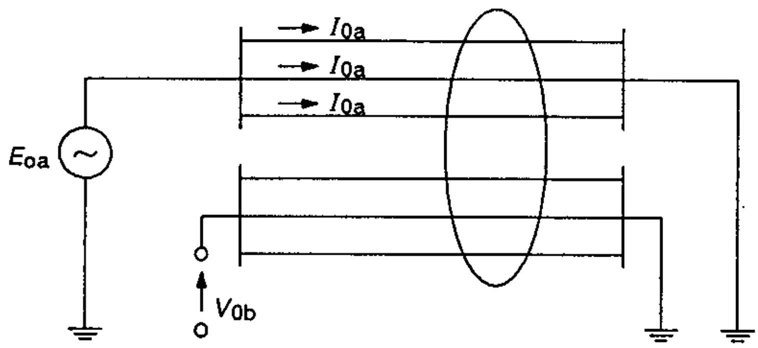



**Fig. 4.5: Mutual coupling of two three-phase lines**

(4.3) $$Z_{0M} = \frac{V_{0b}}{I_{0a}} = 3 \cdot z_M$$

Where $z_M$ is the mutual impedance between two conductors with earth return as defined above.

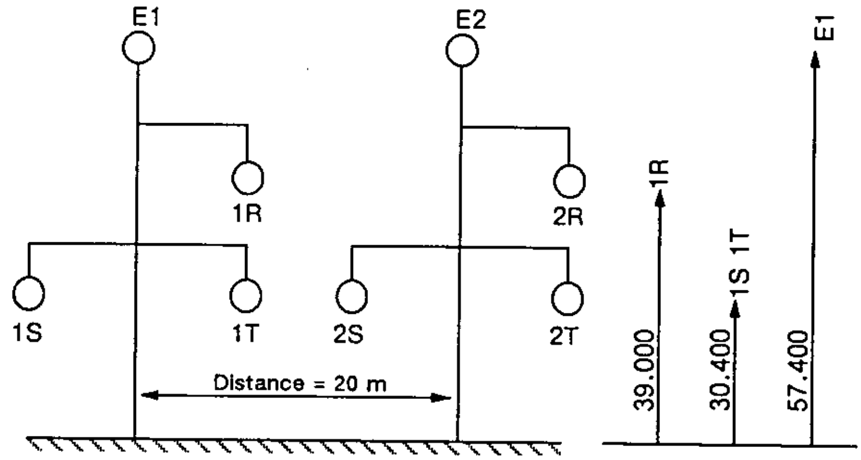
The mutual zero-sequence impedance can be as high as about 70% of the zero-sequence self-impedance when the parallel lines are mounted on the same tower.

The mutual coupling effect has therefore a strong impact on earth fault relaying.

An accurate calculation of $Z_{0M}$ has to consider the real spacings between the conductors of the multi-circuit line and the characteristics, number and location of the earth wires which reduce the mutual coupling effect [11].

Today computer programs are applied to determine the characteristic line impedances. Additionally, the values can be measured as outlined in appendix 3.

The calculated values for a typical 380kV double-line are given below.




Line conductors are 4x240 mm² ACSR
Earth conductor is 240 mm² ACSR

**Fig. 4.6: Parallel 380kV lines**

| | Earth resistivity 100 Ω m | Earth resistivity 1000 Ω m |
|---|---|---|
| Positive sequence impedance (Ω/km) | 0.032 + j 0.303 | 0.032 + j 0.303 |
| Zero sequence impedance (Ω/km) | 0.202 + j 0.88 | 0.236 + j 0.96 |
| Positive sequence capacitance (nF/km) | 12.42 | 12.42 |
| Zero sequence capacitance (nF/km) | 7.95 | 7.95 |
| Zero sequence mutual impedance (Ω/km) | 0.169 + j 0.523 | 0.202 + j 0.599 |
| Pos./Neg. sequence mutual impedance (Ω/km) | 0.01 − j 0.019 | − 0.01 − j 0.019 |
| Positive sequence mutual capacitance (nF/km) | 0.76 | 0.76 |
| Zero sequence mutual capacitance (nF/km) | 3 | 3 |

**Table 4.1: Typical characteristic line data (380kV line of fig 4.6)**

It is to be noted that the zero sequence impedances vary slightly with the earth resistivity. When the values are used to set fault-locators it may therefore be advisable to use measured values. (The measuring method is shown in annex 3).

As shown in table 4.1, there exists also a capacitive coupling between parallel circuits where again only the zero sequence mutual capacitance is significant. It can cause displacement voltages in Peterson-coil compensated networks when lines of this network are conducted at the same tower together with EHV-lines [4.29].

For normal protection calculations the capacitive coupling can be neglected.

## 4.2 Protection problems encountered

### 4.2.1 Mutual coupling of parallel circuits

To study the impact of this phenomenon on protection it is useful to introduce the following classes of networks in accordance with reference [4].

Class 1 networks: Parallel circuits with common positive and zero sequence sources
Class 2 networks: Parallel circuits with common positive but isolated zero-sequence sources
Class 3 networks: Parallel circuits with positive and zero sequence sources isolated.

#### 4.2.1.1 Class 1 networks: Parallel circuits with common positive and zero-sequence sources

This is the normal parallel line case especially when both lines terminate at the same busbar in each substation. The network can in principle always be reduced to the following configuration:

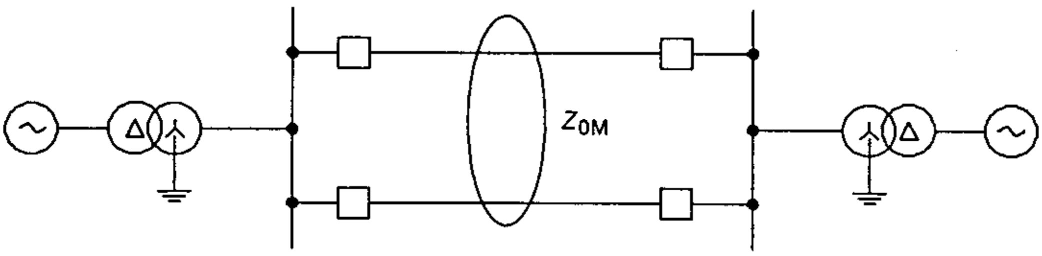



Fig. 4.7: Class 1 parallel circuit

##### 4.2.1.1.1 Impact on distance protection

Distance relaying of ph-ph and three-phase faults is not influenced by the parallel line. For protection of phase-to-earth faults, however, a measuring error occurs. This phenomenon has been studied in a large number of publications [4.1, 4.2, 4.3, 4.6, 4.7, 4.15, 4.16, 4.28].

In principle this error appears due to the fact that the parallel line earth-current ($I_{Ep} = 3 \cdot I_{0p}$) induces a voltage $I_{Ep} \cdot Z_{0M} /3$ into the fault-loop.

The distance relay phase-to-earth units measure:

(4.4) $$Z = \frac{V_{ph-E}}{I_{ph} + k_0 \cdot I_E}$$

$V_{ph-E}$ = phase to earth short-circuit voltage at the relay location in the faulted phase

$I_{ph}$ = short circuit current in the faulted phase

$I_E$ = earth-current

$$k_0 = \frac{Z_{0L} - Z_L}{3 \cdot Z_L} = Z_E / Z_L$$ = earth compensation factor set at the relay

The short-circuit voltage can be calculated as

(4.5) $$V_{ph-E} = I_{ph} \cdot Z_L + \frac{Z_{0L} - Z_L}{3} \cdot I_E + \frac{Z_{0M}}{3} \cdot I_{Ep}$$

(4.6) $$V_{ph-E} = Z_L \cdot \left( I_{ph} + \frac{Z_{0L} - Z_L}{3 \cdot Z_L} \cdot I_E + \frac{Z_{0M}}{3 \cdot Z_L} \cdot I_{Ep} \right)$$

By introducing (4.6) into (4.4) we get:

(4.7) $$Z = Z_L \cdot \frac{I_{ph} + \frac{Z_{0L} - Z_L}{3 \cdot Z_L} \cdot I_E + \frac{Z_{0M}}{3 \cdot Z_L} \cdot I_{Ep}}{I_{ph} + k_0 \cdot I_E}$$

If the relay earth compensation factor $k_0$ is adjusted to the single-line

(4.8) $$k_0 = \frac{Z_E}{Z_L} = \frac{Z_{0L} - Z_L}{3 \cdot Z_L}$$

then the relay measures

(4.9) $$Z = Z_L \cdot \left( 1 + \underbrace{\frac{k_{0M} \cdot I_{Ep}}{I_{ph} + k_0 \cdot I_E}}_{\text{Error}} \right)$$

$I_E$ = earth current of the faulty line
$I_{Ep}$ = earth current of the parallel line

From formula (4.9) it can be deduced:

- The error is proportional to the mutual coupling factor $k_{0M} = Z_{0M} / 3 \cdot Z_L$ .
- The error increases with the parallel line earth current $I_{Ep}$ in relation to the relay current $I_{ph} + k_0 \cdot I_E$
- The relay underreaches when $I_{Ep}$ is in phase with $I_{ph}$ and $I_E$
- The relay overreaches when $I_{Ep}$ and $I_{ph}/I_E$ have opposite signs.

In appendix 4 the change in reach is shown for different fault locations on a parallel line with single infeed. This case demonstrates the worst condition as the ratio of $I_{EP}$ to $I_E$ is highest. For a fault at the remote line terminal the underreach amounts to about 25%.

In the following, three examples are presented to illustrate the effect of mutul coupling on distance relaying. The errors in percentage are calculated using the line data of appendix 4: $k_0 = 0.66$, $k_{0M} = 0.4$

**Fault at the end of a parallel line**

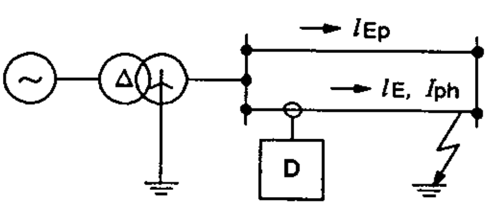



Fig. 4.8

From (4.9) and $I_{ph} = I_E = I_{Ep}$ we get the error:

(4.10) $$\Delta Z = \frac{k_{0M}}{1 + k_0} \cdot Z_L \triangleq 24\% \text{ of } Z_L$$

**Fault at the end of a parallel line, one breaker open**

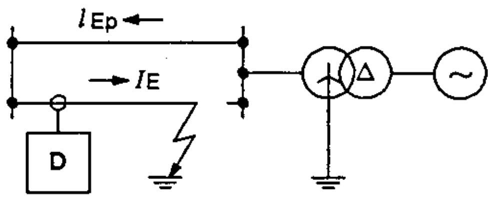



**Fig. 4.9**

From (4.9) and $I_{ph} = I_E = -I_{Ep}$ :

(4.11) $\Delta Z = -\dfrac{k_{0M}}{1 + k_0} \cdot Z_L \triangleq -24\%$ of $Z_L$

**Fault at the end of a parallel line**
**Positive and zero-sequence sources at opposite line ends**

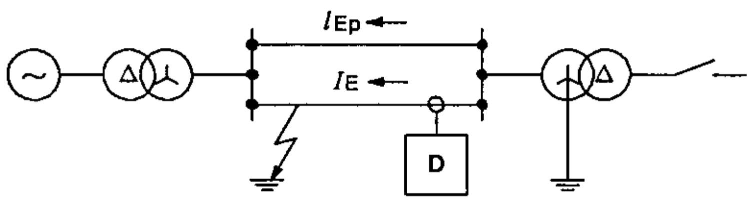



**Fig. 4.10**

From (4.9) and $I_E = I_{Ep} = 3 \cdot I_{ph}$

(4.12) $\Delta Z = \dfrac{3 \cdot k_{0M}}{1 + 3k_0} \cdot Z_L = \dfrac{Z_{0M}}{Z_0} \cdot Z_L \triangleq 40\%$ of $Z_L$

For the setting and behaviour of the distance protection with earth-faults, the case is important where the parallel line is switched off and earthed at both terminals:

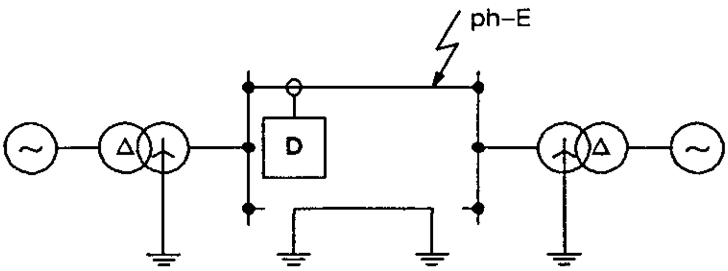



**Fig. 4.11**

The distance protection overreaches considerabely as the earth–impedance is reduced due to the parallel connection of the zero–sequence systems of both lines:

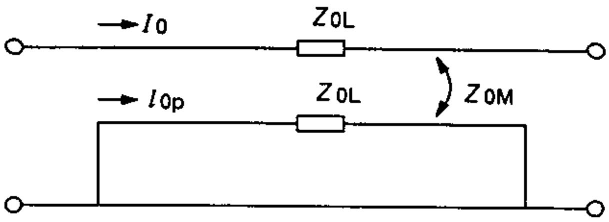



Fig. 4.12

The parallel line zero–sequence current can be calculated as

(4.13) $I_{0p} = -\frac{Z_{0M}}{Z_{0L}} \cdot I_0$ and $I_{Ep} = -\frac{Z_{0M}}{Z_{0L}} \cdot I_E$

By insertion of this $I_{Ep}$ value into equation (4.7) we get the measured relay impedance:

(4.14) $$Z_{\perp} = Z_L \cdot \frac{I_{ph} + \left( \frac{Z_{0L} - Z_L}{3 \cdot Z_L} - \frac{Z_{0M}^2}{3 \cdot Z_L \cdot Z_{0L}} \right) \cdot I_E}{I_{ph} + k_0 \cdot I_E}$$

The measured difference against the single line is then

(4.15) $$\Delta Z = - Z_L \cdot \frac{k_{0M} \cdot \frac{Z_{0M}}{Z_{0L}}}{1 + k_0} \triangleq - 10\% \text{ of } Z_L$$

(with $k_0 = 0.66$ and $k_{0M} = 0.4$)

### 4.2.1.1.2 Setting of distance zones for parallel lines

The distance protection zone reaches vary with the switching state of the parallel line configuration. Below, the configurations and the corresponding formulae for the reach calculation are given for the most important cases:

**Case 1**

Parallel line switched-off and earthed at both line ends.

(4.16) $$Z = x \cdot Z_L \cdot \frac{1 + \left( \frac{Z_{0L} - Z_L}{3 \cdot Z_L} - k_{0M} \cdot \frac{Z_{0M}}{Z_{0L}} \right)}{1 + k_0}$$

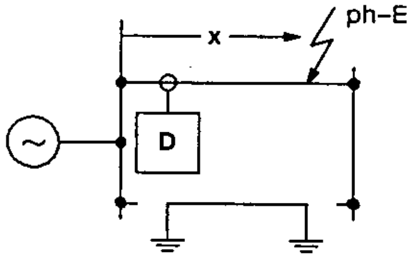



**Fig. 4.13**

**Case 2**

Parallel line switched-off and not earthed or earthed only at one line end.

(4.17) $$Z = x \cdot Z_L \cdot \frac{1 + \frac{Z_{0L} - Z_L}{3 \cdot Z_L}}{1 + k_0}$$

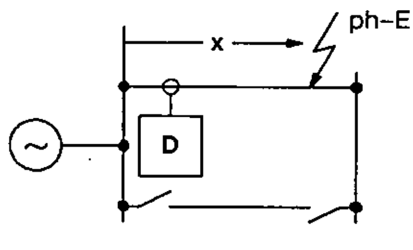



**Fig. 4.14**

**Case 3**

Both lines in service

(4.18) $$Z = x \cdot Z_L \left( \frac{1 + \frac{Z_{0L} - Z_L}{3 \cdot Z_L} + \frac{x}{2 - x} \cdot k_{0M}}{1 + k_0} \right)$$

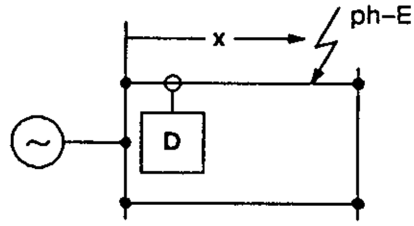



**Fig. 4.15**

In case 1 the lowest impedance is measured, i.e. the highest reach occurs due to the parallel connection of the zero-sequence systems of both lines.

In case 3 the highest impedance is measured which corresponds to the shortest reach.

### Setting of the underreaching zone

The set zone reach should fulfill two criteria:

- it should ensure selectivity, i.e. it should avoid overreach beyond the remote line terminal in case 1.
- it should cover as much of the line as possible, at least 50% plus a safety margin in the most unfavorable case 3.

A possible setting strategy is to set the zone to e.g. 90% of the line length for case 1 and check afterwards if sufficient reach exists in the cases 2 and 3.

The following example shall demonstrate the procedure by using the characteristic data of the 380kV line of page 18.

### Underreaching zone, setting example

Given values: $z_L$ = 0.303 Ohm/km
$z_{0L}$ = 0.88 Ohm/km
$z_{0M}$ = 0.523 Ohm/km

(4.19) $$k_{0M} = \frac{Z_{0M}}{3 \cdot Z_L} = \frac{0.523}{3 \cdot 0.303} = 0.575$$

The distance zone reach is set to 90% of $Z_L$

**Case 1:**

To achieve 90% zone reach also for earth faults, the relay earth fault compensation factor $k_0$ has to be set to

(4.20) $$k_0 = \frac{Z_{0L} - Z_L}{3 \cdot Z_L} - k_{0M} \cdot \frac{Z_{0M}}{Z_{0L}} = 0.29$$

**Case 2:**

The reach in this case can now be calculated by the formula

(4.21) $$90\%\, Z_L = x \cdot Z_L \frac{1 + \dfrac{Z_{0L} - Z_L}{3 \cdot Z_L}}{1 + k_0}$$

where x is the unknown reach and $k_0$ is the set earth factor from case 1: $k_0 = 0.29$. We get: x = 71%.

**Case 3:**

In a similar way we can calculate the reach from the formula

(4.22) $$90\%\, Z_L = x \cdot Z_L \left( \frac{1 + \dfrac{Z_{0L} - Z_L}{3 \cdot Z_L} + \dfrac{x}{2 - x} \cdot k_{0M}}{1 + k_0} \right)$$

As solution of this quadratic equation in x we get: x = 62%.

**Summarizing comment on the underreaching zone setting:**

- A setting adapted to the worst case that the parallel line is switched off and earthed at both ends guarantees absolute selectivity for all switching states.
- The reach (62%) under the normal parallel line service provides only a small (24%) overlapping with the remote end protection.This could be accepted as the coupling is smaller with infeeds from both ends and the remote end distance zone tends to overreach in the same case (see annex 4). -

Other practised setting strategies are:

- Avoid earthing at both ends of the switched-off line (earthing only at one side). The underreaching zone could then be adjusted to let say 85% of the single line (case 2) and a reach of 72% in case 3 could then be achieved.
- The case of the switched-off and double-earthed parallel line is assumed to occur seldom. An overreach in this case is accepted bearing in mind that the overreach into the following lines, considered as distance (km), is normally heavily reduced due to infeeds at the remote substation.
- The probability of a definite outage of a line due to zone overreach is further reduced when autoreclosure is practised. Therefore, also with this strategy, an adaption of the setting to the single line (case 2) could be justified.
- A further possibility to solve the selectivity problems is to apply an overreaching distance protection scheme using telecommunication.

The choice of the strategy must finally be based on the local conditions and the service experience of the utility.

**Setting of the overreaching zone**

The overreaching zones for back-up or permissive overreaching distance protection schemes must at least safely cover 100% of the line with a safety margin of about 20%. This must be guaranteed for the most unfavorable condition of case 3. For cases 1 and 2 the overreach would then be higher. It has to be considered that, with the parallel line switched-off and earthed at both ends, the second zone could then overlap with the second zone of a following line and endanger the zone grading selectivity.

However, in normal practice this reach extension provides no problem as the overreach into the following lines is anyway reduced by the intermediate infeeds at the remote substation.

The reach extension can be estimated by subtracting the measured impedances of the above defined cases 3 and 1 (equations (4.16) and (4.18)).

(4.23) $$\frac{Z_{\text{case 3}} - Z_{\text{case 1}}}{Z_L} = \frac{k_{0M} \cdot \left(1 + \frac{Z_{0M}}{Z_{0L}}\right)}{1 + k_{0p}}$$

Where $k_{0p}$ is the relay earth-compensation factor set for the parallel line condition

(4.24) $$k_{0p} = k_{0s} + k_{0M}$$

$$k_{0s} = \frac{Z_{0L} - Z_L}{3 \cdot Z_L}$$ Earth compensation factor for the single line

$$k_{0M} = \frac{Z_{0M}}{3 \cdot Z_L}$$ Mutual coupling factor

**Calculation example:**

Given values: $z_L$ = 0.303 Ohm/km
$z_{0L}$ = 0.88 Ohm/km
$z_{0M}$ = 0.523 Ohm/km

$$\frac{Z_{\boxminus} - Z_{\underline{\boxminus}}}{Z_L} = 0.39$$

This result means that in this case a second zone set to let say 150% of $Z_L$ would then have a reach of 209% of $Z_L$.

This is further illustrated by the following zone grading example.

A series connection of a double– and a single line is assumed.

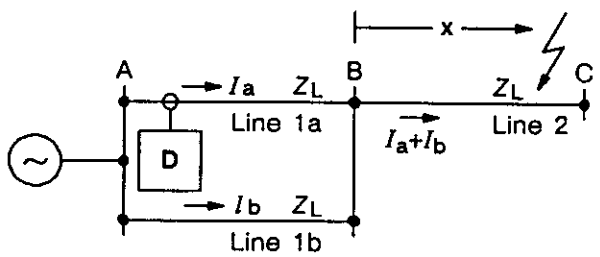



**Fig. 4.16: External fault on a following line**

The relay R measures the following impedance for a fault on line 2 in the distance x% of $Z_L$ from station B (series connection of the defined cases 3 and 2).

$$(4.25)\qquad Z_2 = Z_L \cdot \frac{1 + \dfrac{Z_{0L} - Z_L}{3 \cdot Z_L} + k_{0M}}{1 + k_{0p}} + 2 \cdot Z_L \cdot \frac{1 + \dfrac{Z_{0L} + Z_L}{3 \cdot Z_L}}{1 + k_{0p}} \cdot x$$

Where $k_{0p}$ is the set compensation factor adapted to the parallel line as defined above.

$k_{0p} = 0.63 + 0.52 = 1.15$

For the assumed second zone setting of $Z_2$ = 150% $Z_L$ we can calculate the reach x on line 2 from the equation (4.25).

We get x = 33% as reach on the following line during the normal parallel line service.

When line 1b is switched–off and earthed at both line ends the relay R will measure an earth–fault on line 2 according to the following formula (series connection of the defined cases 1 and 2):

$$(4.26)\qquad Z_2 = Z_L \cdot \frac{1 + \dfrac{Z_{0L} - Z_L}{3 \cdot Z_L} - k_{0M} \cdot \dfrac{Z_{0M}}{Z_{0L}}}{1 + k_{0p}} + Z_L \cdot \frac{1 + \dfrac{Z_{0L} + Z_L}{3 \cdot Z_L}}{1 + k_{0p}} \cdot x$$

For the unchanged zone setting of $Z_2$ = 150% of $Z_L$ and $k_0$ adapted to the parallel line $k_{0p}$ we get now a reach on the following line of x = 117%, i.e. the zone would reach beyond the station after the next.

**Summarizing comment on Overreaching-zone setting:**

- The reach setting must be adapted to guarantee back-up for at least 100% line length plus a safety margin of about 15 to 20%. For remote back-up purposes longer reaches graded to the protection of the following lines are desirable.
- The earth-fault compensation factor must be adjusted to the parallel line service where the highest earth-fault impedances occurs.
  This requirement can be fulfilled by $k_0$-setting when separate $k_0$-factors can be set for the under- and overreaching zones.
  If the relay has a common $k_0$-factor for all zones, the $k_0$-factor set for the underreaching zone has to be taken over, and the overreach-zone setting ($Z_2$) has to be adapted (enlarged) if the safety margin of about 15 to 20 % overreach over the next station is not achieved.
  In the above formulae 4.23 to 4.26, the $k_0$-factor chosen for the first zone has to be applied instead of $k_{0P}$.
- For the service case of one line being switched-off and earthed at both ends the appearing reach extension into the following lines has to be checked.
  Unselectivity in the zone grading is normally not to be expected when infeeds exist at the remote substation because they reduce the overreach considerably.
- The series-connection of parallel lines and the impact of infeeds provide problems for the setting of remote back-up zones [4.31]. Local back-up protection concepts should be preferred for these complex transmission networks.

### 4.2.1.1.3 Compensation of Mutual Coupling

The conventional distance relays measure phase-to-earth faults according to the formula (4.7).

The measuring current is

$$I = I_{ph} + k_0 \cdot I_E$$

where $k_0$ is the earth-compensation factor.

The induced voltage from the earth-current of the parallel line

$$V_{OM} = I_{EP} \cdot Z_{OM}/3 = I_{OP} \cdot Z_{OM}$$

can be compensated by adding a relevant further term to the relay measuring current proportional to the earth-current of the parallel line ($k_{OM} \cdot I_{Ep}$).

Formula (4.7) then changes as follows:

$$(4.27) \qquad Z = Z_L \cdot \frac{I_{ph} + \frac{Z_{OL} - Z_L}{3 \cdot Z_L} \cdot I_E + \frac{Z_{OM}}{3 \cdot Z_L} \cdot I_{Ep}}{I_{ph} + k_0 \cdot I_E + k_{OM} \cdot I_{Ep}}$$

It is obvious that the relay measures the correct impedance $Z_L$ when:

$$(4.28) \qquad k_0 = \frac{Z_{OL} - Z_L}{3 \cdot Z_L} \quad \text{and} \quad k_{OM} = \frac{Z_{OM}}{3 \cdot Z_L}$$

With this mutual compensation, the relays at the faulted line measure correctly. However, the relays on the healthy parallel line measure incorrectly and tend to overreach. This is demonstrated in detail in annex 5.

It is therefore necessary to block the distance relays or to switch-off the mutual compensation on the healthy parallel line relays.

One solution is to compare the earth-currents of both lines (earth-current scales) and to release the compensation only on the line with the higher earth-current which is always the faulted line.

This compensation method requires a cross-connection of the earth-current wires of parallel feeder bays in the substation and the additional current-comparison equipment. This may be one reason why the mutual compensation is not very often applied for distance relaying. The other reason is that the problem can be normally overcome by proper zone setting or by application of command protection systems.

The compensation is however in any case necessary for fault locators to enable a correct distance-to-fault determination.

### 4.2.1.2 Class 2 networks: Parallel circuits with common positive but isolated zero-sequence sources

The following network is a typical representative of class 2 networks.

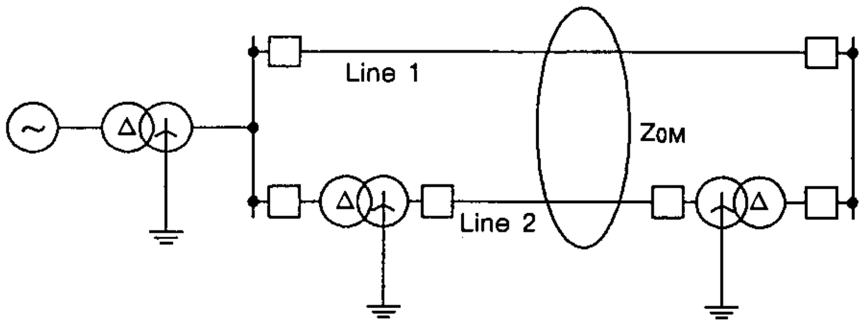
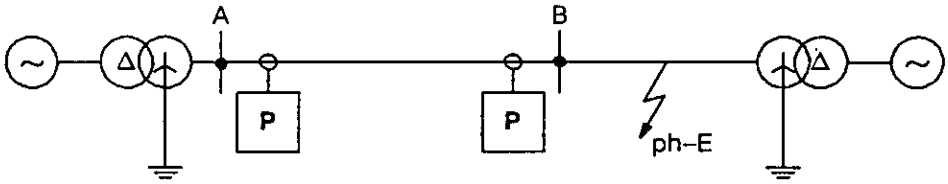



Fig. 4.17: Class 2 network

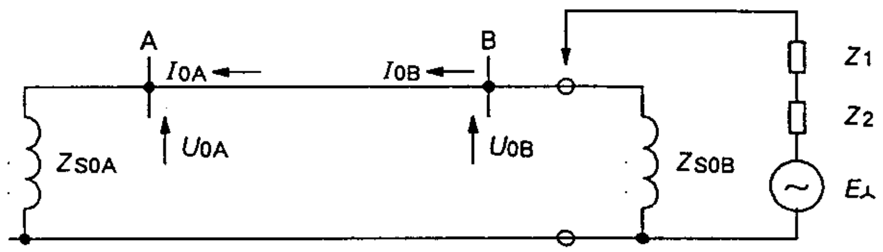
In these network types the mutual coupling will not only influence the distance measurement but will also cause problems with directional earth fault relays in the isolated zero-sequence system of the parallel line.

The behaviour of the earth-fault relay can be analyzed in the zero-sequence system replica.

In the case without mutual coupling, when an external fault is correctly detected, the phase-relations of zero-sequence voltage $V_0$ and current $I_0$ at each line end are as outlined in the following figure 4.18.




a) External earth-fault, single-line diagram




b) External earth-fault, zero-sequence system

Fig. 4.18

For an earth-fault on a mutually coupled parallel circuit without common zero-sequence sources the replica circuit is shown in the next figure 4.19.

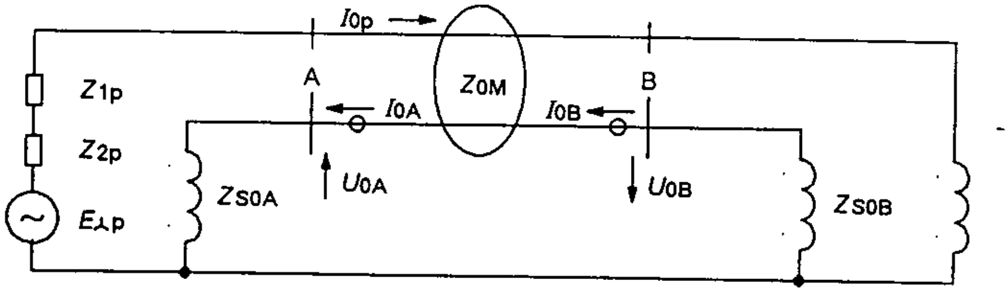



**Fig. 4.19: Earth-fault on a parallel circuit with isolated sources in the zero-sequence system**

The mutually induced current circulates in the isolated zero-sequence system and generates at both line ends voltages comparable to an internal earth-fault.

From these considerations can be concluded that sensitive directional zero-sequence relaying can normally not be applied in class 2 networks.

Similar as with distance relaying on parallel lines a supplementary earth-current comparison scheme could be applied to block the earth-fault relays on the line with the lower earth-current when both ends of the parallel line are accessible in the same substation.

**Summarizing comment on relaying of class 2 networks**

- For distance protection, the comments on class 1 networks apply also here.
- Sensitive directional earth-fault protection with zero-sequence current- or voltage- polarized relays can normally not be applied in circuits with isolated zero-sequence systems.
  Instead, phase-comparison or negative-sequence polarized relays can be recommended [4.5].

### 4.2.1.3 Class 3 networks: Parallel circuits with positive and zero sequence sources isolated

A representative class 3 network is shown in the following figure

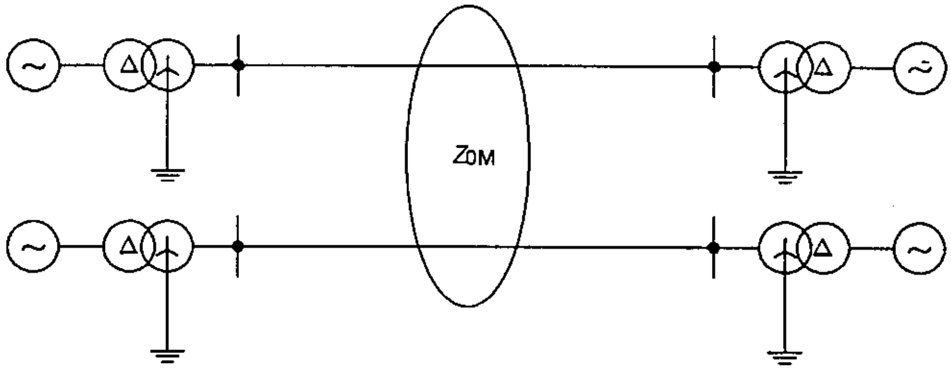



**Fig. 4.20: Parallel circuits with isolated sources**

This situation does normally not occur with parallel lines of the same voltage level because transmission networks are operated as meshed systems.

Class 3 networks exist mainly where lines of different voltage levels are mounted at the same towers.

Naturally, all the problems previously discussed for class 1 and 2 networks apply also here. The difference against class 2 networks is that compensation methods can not be applied. Earth-current comparison at lines with different voltage levels is usually not practised. In most cases it will even technically not be possible when the lines end at different substations.

For the application of distance protection, it has to be considered that, as shown in figure 4.21, a parallel connected zero-sequence system exists that reduces the measured fault impedance, i.e. the protection on the faulted line tends to overreach.

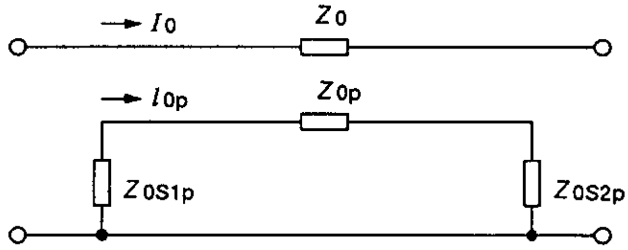



**Fig. 4.21: Zero-sequence replica circuit of two mutually coupled lines with isolated zero-sequence sources**

The parallel line zero-sequence current can be determined from figure 4.21:

(4.29) $$I_{0p} = -\frac{Z_{0M}}{Z_{0S1p} + Z_{0p} + Z_{0S2p}} \cdot I_0$$

If we insert $I_{0p}$ into equation (4.7) we get a similar formula as (4.14).

(4.30) $$Z_{\#} = Z_L \cdot \frac{I_{ph} + \left(\frac{Z_{0L} - Z_L}{3 \cdot Z_L} - \frac{Z_{0M}^2}{3 \cdot Z_L(Z_{0S1p} + Z_{0p} + Z_{0S2p})}\right) \cdot I_E}{I_{ph} + k_0 \cdot I_E}$$

The measured impedance difference against a line without parallel circuit is then

(4.31) $$\Delta Z = -Z_L \cdot \frac{Z_{0M}^2}{3 \cdot Z_L(Z_{0S1p} + Z_{0p} + Z_{0S2p})(1 + k_0)}$$

This influence has to be checked for each individual case. The zone setting must be adapted like with class 1 parallel lines.

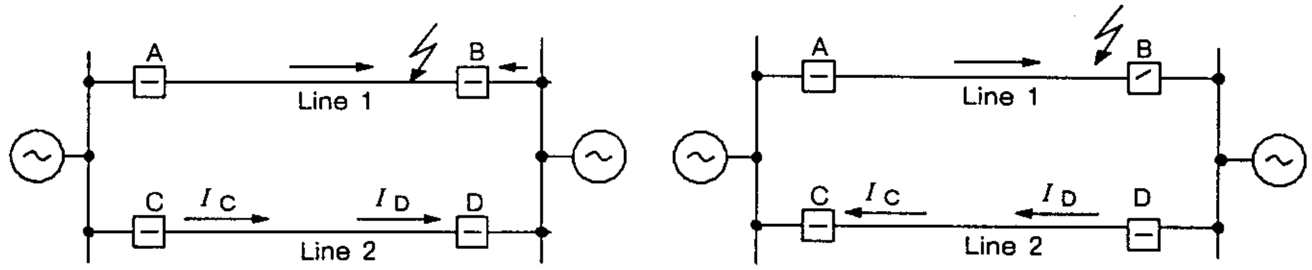
**Summarizing comment on relaying of class 3 networks**

- Class 3 mutually coupled lines belong normally to power systems of different voltage levels.
- Compensation methods can usually not be applied.
- The impact on the zone reach of distance relays has to be estimated in each individual case.
- $V_0$- and $I_0$- polarized directional earth-fault relaying cannot be applied. Negative sequence polarization can alternatively be considered.
- Differential or phase comparison protection can be recommended as these protection versions are safe against mutual coupling.

### 4.2.2 Current reversal effect

Non-simultaneous fault clearance on parallel transmission circuits can cause fault current reversal on healthy lines. This phenomenon can cause a racing between protection directional and carrier signals and can result in a false operation in the worst case.

The following figure demonstrates the problem.




**a) Initial situation after fault inception** **b) Situation after opening of the CB in B**

**Fig. 4.22**

In the initial situation after fault inception the fault-current flows from C to D on the healthy line. It can now occur that breaker B opens before breaker A because the protection in B operates faster due to the higher short-circuit current or because the fault is out of the underreaching zone of the protection in A. In this case the fault current on line 2 reverses. This can cause racing problems in directional comparison protection schemes.

A permissive scheme will behave as follows:

The relay in C initially sees the fault in forward direction but does not trip as no signal is received from the remote end. When the current reverses, the relay in D will send an enable signal to C. If now the directional relay has not changed to reverse direction before the signal is received, a false trip will occur.

The relay in D initially sees the fault in reverse direction and, therefore, does not trip though it receives a release signal from the remote end relay.

When the current reverses, the directional decision of relay D changes from reverse to forward. If now the release signal from relay C still hangs-on, relay D will issue a false trip.

Short parallel lines provide the worst condition because the relative overreach of the tripping zone is highest in this case. The situation is further aggravated when the parallel line is series compensated (see 7.4.1.4).

To avoid false operation under these conditions, a so called TRANSIENT BLOCKING function (also called Current Reversal Guard) is necessary.

This feature allows fast tripping for a short time interval (about 40ms) after fault inception but slows down or blocks the protection before breaker B opens, i.e. before the current reversal can occur.

### 4.2.3 Double- and intercircuit-faults on multi-circuit lines

Double faults that involve the two circuits of a parallel line occur predominantly where the multiple-circuits are mounted on the same tower.

When lightning hits such a transmission system, severe voltages appear on all insulator strings and one or more can flash over, creating single or multiple line-to-earth faults. The time between separate faults is only a few milliseconds. Thus, these double faults can be considered as simultaneous.

The probability of double faults depends widely on the tower construction and increases as the footing resistance increases. Available statistics and replies to a CIGRE-questionnaire of 1989 show that about 10 to 20% of all line-to-earth faults involve two circuits of a parallel line. However, values up to 50% have also been reported [4.21].

Further reasons for multiple faults are conductor galloping or broken wires, flying debris or bush fire under the line.

In this case flash-over faults can occur that short-circuit the conductors of two parallel circuits with or without earth-connection. This can cause quite unusual fault current distributions which have a partly uncalculable impact on protection systems [9, 4.8].

The worst condition is given with so called intersystem faults, that is when a short-circuit occurs between two transmission systems of different voltage levels. In this case the protection behaviour is practically unforseeable and can normally only afterwards be analysed by computer studies [4.24]. Fortunately, these extreme fault situations are seldom and only one or two cases in 10 years per utility have been reported.

For the protection engineer the most frequently appearing double earth-fault with footing points at different circuits is more interesting.

The standard situation is shown in the following figure 4.23.

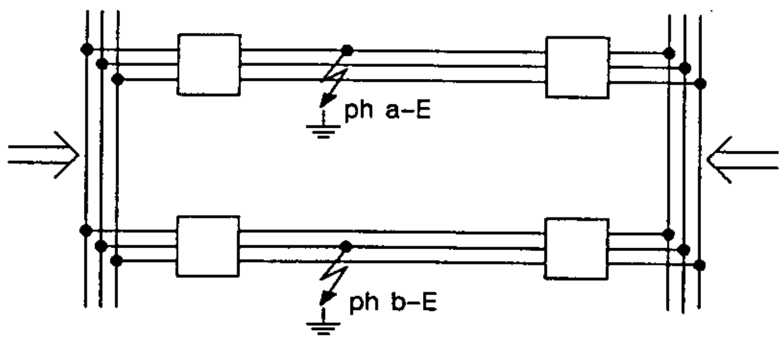



**Fig. 4.23: Double-fault on a parallel line**

A phase-selective tripping and automatic reclosure is desirable in this case to keep one complete three-phase transmission system in service to maintain system stability.

The phase selection for tripping should therefore not be controlled by the protection starting elements because they have a high reach and will normally see both faults at the same time and consequently initiate a three-phase tripping of both lines. It is better to use distance zones with a short overreach (e.g. 20%) for phase selection. Naturally, one measuring unit per phase must be available, that is at least a three-system distance relay must be used. At full scheme distance protection schemes the phase-to-phase units must be inhibited in this case, e.g. by the earth-current detector, to prevent an adverse effect on the phase selection.

If the two earth-faults are located at a tower close to the remote line terminals they can both be detected also by the overreaching distance zones and phase selective tripping will then not occur. However, due to the positive or zero sequence infeeds at the remote substation this is very unlikely in meshed transmission networks.

To get phase selectivity for a hundred percent of the line length for this kind of double-fault, a phase-segregated protection scheme must be applied. Either non-unit or unit protection schemes are suitable.

The analysis of further simultaneous faults on multi-circuit lines, especially when different fault types are combined, is rather complex. They are normally not considered for the practical design and selection of the protection system.

Computer programs, however, are available to study the protection behaviour under such conditions. The treatment of this subject is beyond the scope of this application guide which is aimed at the application engineer. The theorically interested reader is referred to the available publications [9, 4.8, 4.24] .

## 4.2.4 Dissymmetries on double-circuit lines

The dissymmetries of non-transposed transmission lines cause circulating currents in a multi-circuit-line configuration. Negative and zero-sequence currents in the order of 5% line-loadcurrent can appear. This dissymmetry effect is amplified by the series compensation of lines.

The unbalanced insertion of series-capacitor banks can aggravate this unbalance even more. Negative to positive sequence current ratios of more than 25% have been reported [4.3].

Sensitive earth-fault relays have to be set above these unbalance currents to avoid false pick-up.

Load currents on untransposed EHV lines may also induce circulating zero sequence currents in parallel HV-systems if they are mounted on the same tower.Sensitive earth-fault protection may be adversely affected when the HV system is highly resistive or resonantly earthed. Special solutions may be necessary under these circumstances [4.20].

## 4.3 Protection schemes

The selection of a suitable protection scheme for multi-circuit lines is controlled by a larger number of decision factors like

- necessary operating fault clearing time,
- available signal transmission channels,
- autoreclosure practice (single-, 3-pole),
- experience with practised protection philosophies,
- cost.

It is therefore natural that a wide variety of solutions exist for the problems discussed in the previous chapter. In the following it will be decided between non-unit and unit-protection schemes as defined in chapter 3.

### 4.3.1 Non-unit protection

This kind of line protection comprises all distance and all directional and non-directional earth-fault protection relays with or without telecommunication.

#### 4.3.1.1 Distance protection without telecommunication

Signalling links can be saved when no severe stability problems exist and end-line faults can be cleared in second zone time (e.g. 400ms). It has, however, to be considered that, due to the mutual coupling effect, the 1st zone can be considerably reduced.

To achieve fast fault clearing the distance protection is in some countries operated with zone-extension controlled by the autoreclosing scheme (AR). The 1st zone is extended to overreach the remote line terminal when the autoreclosure is ready. During the AR-dead-time the zone is then switched-back to underreach. Thus, all transient faults can be cleared instantaneously, at the expense of a short line outage.

The zone setting is shown in the following figure 4.24.

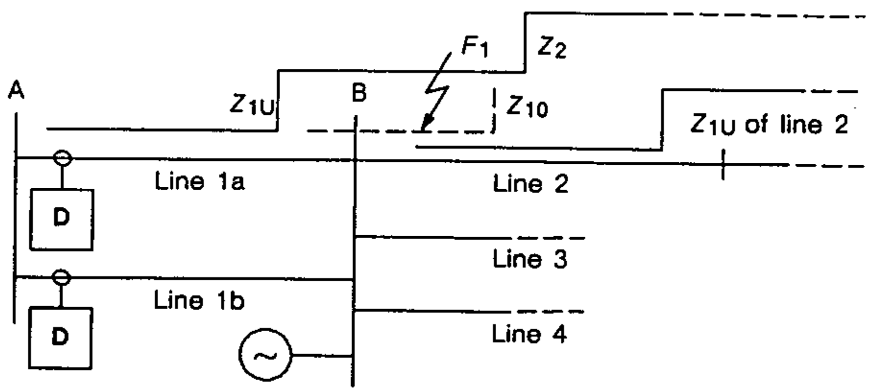



**Fig. 4.24: Distance protection with AR-controlled zone switching**

It has to be considered that the distance protections in station A can also perform an autoreclosure for an external fault on line 2 just behind the remote station B in location F1. The probability for this unnecessary AR is, however, extremely low as the overreach of $Z_{10}$ is heavily reduced by the usually existing infeeds in station B.

The zone setting for phase-to-earth faults has to be carefully chosen as outlined in section 4.2.1.1.2. A longer reach of $Z_{1U}$ could be achieved by using a mutual compensation supplement for the distance protection. Such devices are offered by some manufacturers. This however would require crossconnecting the earth-current from the neighbouring bay of the parallel line as mentioned in 4.2.1.1.3.

The following phenomenon also justifies the decision normally not to compensate the mutual coupling effect.

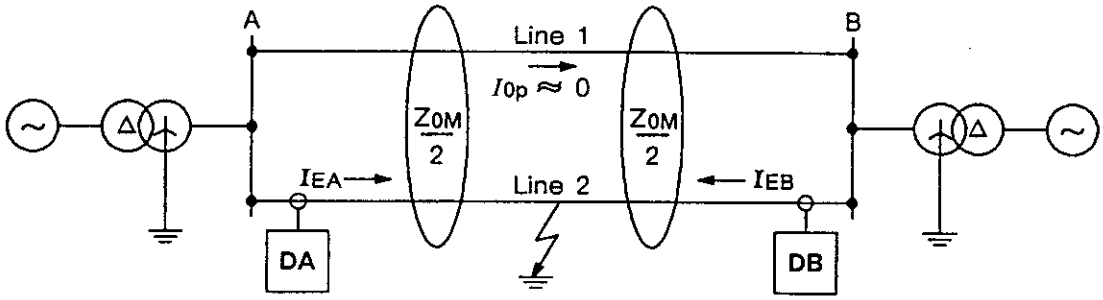



**Fig. 4.25: Mid-line fault, equal sources mutual coupling**

If the fault occurs near the middle of line 2, the earth current on line 1 is relatively small when the zero-sequence source impedances in A and B are of the same order of magnitude. The coupling effect is then small and a good overlapping of the underreaching zones of relays DA and DB is given. That means that the mutual coupling impact is only effective for faults near the line terminals. In this case, however, the protection nearer to the fault will trip and open the circuit breaker. Thereafter the situation of the figure 4.26 occurs.

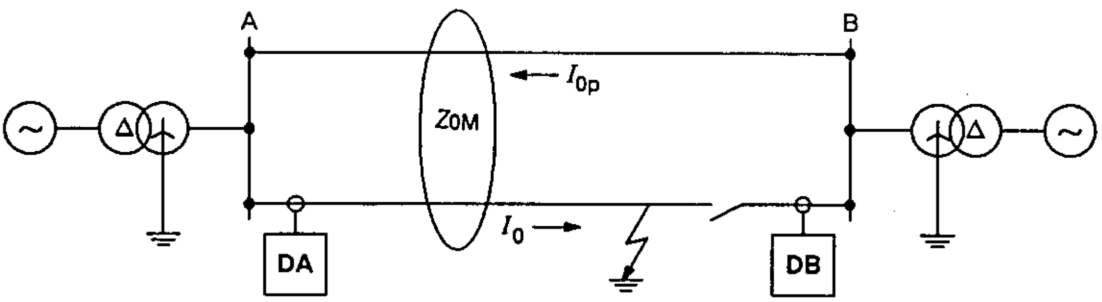



**Fig. 4.26: Mutual coupling, overreach condition**

The zero-sequence current now flows in opposite directions in both lines, i.e. the distance relay DA extends and may trip desirably also.

In this case the fault is cleared in a cascaded tripping with an additional delay in the order of about 100ms (protection- plus CB-time). This is in many cases acceptable.

In cases where the zero-sequence source impedances are of a different order of magnitude, the mutual coupling is also effective for mid-line faults as zero-sequence current flows from the weak to the strong source line side on the parallel line. This is illustrated in the following figure 4.27.

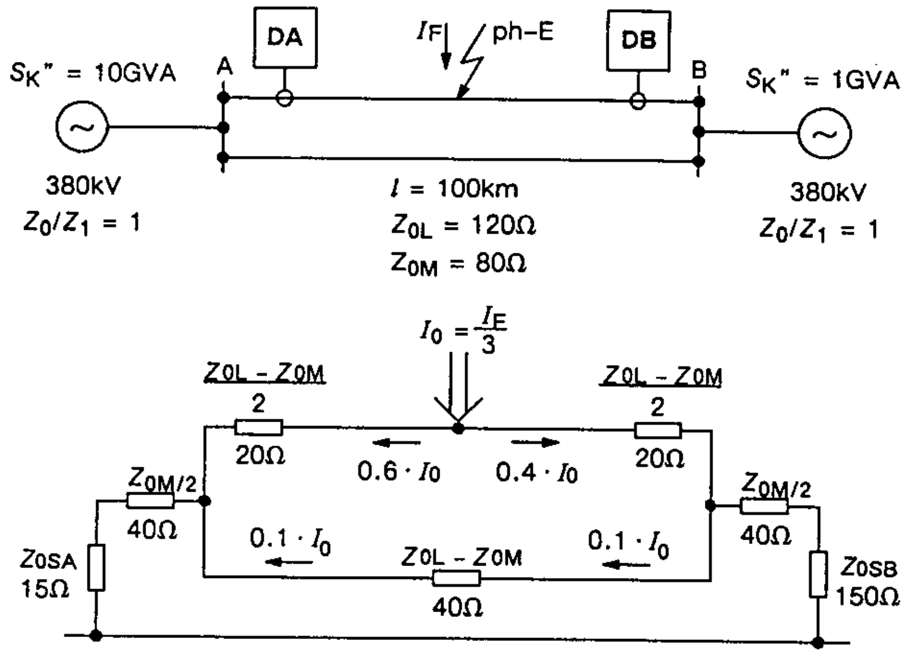



**Fig. 4.27: Parallel line, Mid-line ph-E-fault with unequal zero-sequence sources**

At the weak zero-sequence terminal the line currents flow in opposite directions. Relay DB at this line-end will therefore overreach and trip safely. Protection DA at the other line-end will initially see the fault and trip or trip in cascade.

As a summary of the above discussion it can be developed that even with a short setting of the underreaching zone (e.g. adapted to the condition of the parallel line being switched off and earthed at both ends, that is about 60 to 70% $Z_L$) a dependable fault clearing is ensured, at least in a cascaded tripping.

Probably the most frequent practice is to set the underreaching zone to about 75 to 80% of the single-line impedance and to rely on the zone reduction due to remote infeed when the parallel line is switched off and earthed at both line terminals or, as an alternative way, to avoid this double earthing.

Cases where the parallel lines do not end at the same busbar at both line ends need special consideration because the distance protection can overreach under certain conditions. This is demonstrated in figure 4.28.

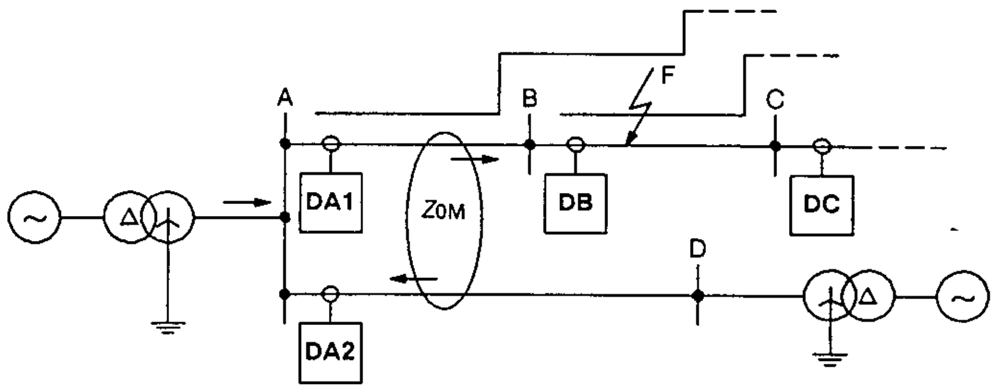



Fig. 4.28: **Distance protection of mutually coupled lines not ending at the same bus at both terminals**

The earth-currents in line A-B and A-D flow in opposite directions. The relay DA1 therefore tends to overreach. The weaker the infeed in A is compared to D, the higher the overreach.

The situation can be even worse when the mutually coupled lines have different sources at both ends.

In these cases a reduction of the underreaching zone according to a short-circuit study could be feasible. A better solution is to use a permissive overreaching or blocking distance protection scheme. Compensation of the mutual coupling may also be tried where the lines have a common bus at least at one end.

### 4.3.1.2 Directional and non-directional earth-fault relaying

This kind of protection is used in many cases as back-up protection with definite or inverse time delay.

The application on parallel lines with common bus at both ends provides normally no problems. When the lines terminate at separate buses the directional sensing may be adversely affected. This has then to be investigated according to the rules outlined in section 4.2.1.2. Less sensitive setting or the use of negative sequence directional sensing may be a solution [4.4, 4.5].

### 4.3.1.3 Distance protection with telecommunication

All types of under- and overreaching command (transfertrip) protection schemes can be applied when the parallel line is commonly bussed at both ends.

For the underreaching schemes similar mutual coupling considerations apply as for distance relays without telecommunication.

Overreaching methods are in principle the better solutions against mutual coupling problems. However, the protection operation then depends completely on the signal transmission channel.

Zone packaged distance protection schemes are desirable in this case with an additional independent underreaching zone. The latter could be set relatively short, e.g. to about 70% line length in order to avoid overreach in any case.

In cases where the mutual coupling effect cannot be clearly estimated, that is when the parallel line is not commonly bussed at both ends or even worse, when lines of different power systems run parallel, overreaching schemes are to be preferred.

As discussed earlier (see section 4.2.3), the phase-selection for tripping should not be controlled by starting elements or zones (when single-pole autoreclosure is practised on parallel lines). Instead distance zones with short overreach should be used for this purpose. Consequently a zone acceleration scheme is preferable to an underreaching scheme that uses the starting zone as the permissive function.

Phase segregated non-unit distance protection schemes would be the best solution. They are, however, seldom applied as three signal channels have to be provided in each direction per line. This is on one hand expensive and on the other hand the band width is normally not available with power line carrier-transmission systems. In the case of radio-links or with the future, more frequent application of optical fibres, phase segregated schemes could become more popular.

#### 4.3.1.4 Directional comparison earth-fault protection

This protection type combines the directional decision of earth fault relays at both line terminals through a signal transmission channel in a permissive or blocking mode. Both types are in principle suitable also for parallel lines.

Negative- or zero-sequence directional relays are in use. The zero-sequence polarizing quantity can be voltage or current or both (dual polarized relays).

The zero-sequence polarization can be applied without restrictions for parallel lines with a common bus at both ends.

Parallel circuits with isolated zero-sequence sources can create problems with zero-sequence polarization as explained in section 4.2.1.3. Negative-sequence directional relays should then be chosen [4.5].

The pick-up level of the earth-fault detectors should not be set too sensitive to avoid spurious operation on circulating unbalance-currents or charging current.

The following figure 4.29 shows the effect of the capacitive zero-sequence current of an unfaulted parallel line on directional-earth relay operation.

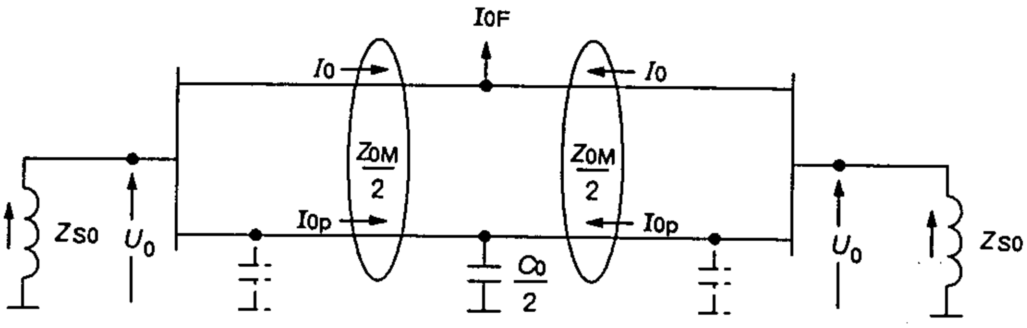



**Fig. 4.29: Impact of charging current on directional earth-fault relaying**

The zero-sequence current $I_{0p}$ is approximately

$$I_{0p} \approx -\frac{j\frac{X_{0M}}{2}\cdot I_0}{-j\,2\cdot X_{0C}} = \frac{X_{0M}}{X_{0C}\cdot 4}\cdot I_0 \quad \text{with} \quad X_{0C} = -j\frac{1}{\omega C_0}$$

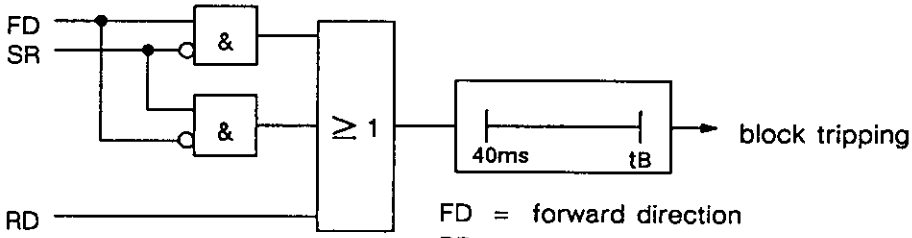
Consequently the zero-sequence currents on the faulty and on the non-faulty parallel line have the same direction. As the polarizing zero-sequence voltage is the same for both circuits, the healthy line relays will falsely sense an internal fault.

For long transmission lines this capacitive current can be relatively high compared to the minimum fault current. A less sensitive setting is then not the appropriate solution.

In case of very long lines (300 to 400km) a supplementary device can help that compares the earth-currents in both circuits of the parallel line and blocks the relay with the lower earth-current which is always the healthy line.

Directional comparison schemes must be equipped with a transient blocking function to avoid false operation in case of current reversals (see section 4.2.2).

The usual function logic is shown in figure 4.30.




FD = forward direction
RD = reverse direction
SR = release signal received from the remote end
tB = transient blocking time

**Fig. 4.30: Transient-blocking logic circuit**

## 4.3.1.5 Directional comparison travelling wave protection

These relays use the sudden changes in voltage and current at fault inception to determine the fault directon (see also section 7.4.2.1):

Directional criterion: $\Delta U \times \Delta I$

$\Delta U$: prefault voltage minus fault voltage

$\Delta I$ : prefault current minus fault current

The directional decisions are then used to set-up a directional comparison scheme via a signalling link in the conventional way.

These relays measure very fast (below a quarter-cycle) and the total scheme operating time can be well below one cycle if fast signal transmission channels are available.

In principle this protection type can also be used with multi-circuit lines. It has however to be considered that power system faults will also induce travelling waves on parallel lines due to the mutual coupling effect. The pick-up sensivity of the directional detectors must therefore not be set too sensitive. Another philosophy is to apply the travelling wave protection only for phase-to-phase faults, thus avoiding mutual coupling problems, and to supplement a separate zero- or negative-sequence directional earth-fault protection.

As the travelling wave protection senses the first sudden changes of the short-circuit quantities and then seals-in for a certain time, it can by principle not detect simultaneous or sequential faults that involve both circuits of a parallel line. An independent main or back-up protection must therefore be provided for these fault-types.

### 4.3.2 Unit protection schemes

This kind of protection compares directly the in- and out-flowing currents of a line either as phase-comparison or as differential protection. Both types are available as composite current or as phase segregated version.

The composite-type uses a measuring quantity which is a weighted mixture of the phase currents ($I_M = k_1 \cdot I_a + k_2 \cdot I_b + k_3 \cdot I_c$) or the symmetrical components ($I_M = k_1 \cdot I_1 + k_2 \cdot I_2 + k_0 \cdot I_0$). This different weighting of currents implies that a fixed phase preference exists.

If a double fault occurs on a parallel line, that involves different phases on both circuits, then the relay operation depends on the condition whether the internal fault is on a higher or lower weighted phase and of the total fault-current distribution. The case may occur that the protection on one line can not operate before the protection on the parallel line has operated and one fault point is cleared.

The composite type relays further need an additional phase-selector when single-pole autoreclosure is practised. It can be an overcurrent, undervoltage or impedance measuring system. Non of these selectors, however, can guarantee a secure phase-selection in the case of simultaneous faults that involve both circuits of a double-circuit line, as previously discussed with distance relays.

Phase-segregated types do not have such restrictions and are therefore ideally suitable for multi-circuit lines.

**Advantages of phase segragated unit protection schemes for the application with parallel lines:**

- Instantaneous clearance also of double faults involving both circuits.
- Safe against mutual coupling effects.
- Hundred percent phase selective for all kinds of single and multiple faults.

When a phase segregated protection is used as main protection, the second or back-up protection should also be set-up phase selective or should be time-delayed for earth-faults to avoid a probable cancelling of the correct phase selection.

It must however be mentioned that unit protection schemes also have disadvantages against distance protection schemes. They need a more expensive wide-band signalling channel and their reliability depends completely on it. Further, unit protection does not provide back-up for faults out of the protection range defined by the CTs at both line ends. Some sort of distance or overcurrent relay is therefore additionally necessary in any case.

### 4.3.2.1 Phase comparison protection (PCP)

This type of protection can be used together with power line carrier channels up to about 300km as composite current version and up to about 200km as phase-segregated version. In the latter case the reach is reduced as 3 tones have to be transmitted and this requires a nine-fold carrier sending power for the same signal to noise ratio. Due to the fact that only phase positions, i.e. current zero-crossings must be transmitted, the channel requirement is moderate. One rectangular-wave comparison signal needs only about 1kHz bandwidth, i.e. the three tones of a phase segregated PCP can easily be transmitted in a standard 4kHz voice-frequency channel.

The single-signal transmission for a composite-type PCP needs only about 1kHz. This allows transmitting additional command signals in the same 4kHz, the so called, voice-plus channel.

In some cases, where a second main protection is provided, it is accepted that the signals of the two circuits of a parallel line are transmitted through one common channel.

The better solution is to transmit the command and measuring signals combined in one voice-plus channel and to cross the signals for a parallel line as follows.

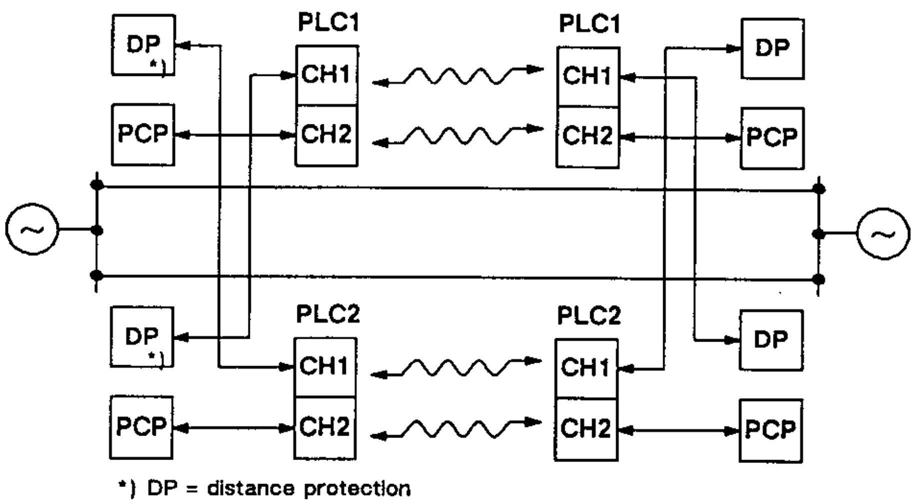



**Fig. 4.31: Protection signalling for a parallel line**

Where radio-links or optical fibre cables can be applied, a high bandwidth for numerous signalling channels is available. Thus, phase-segregated protection should be preferred.

### 4.3.2.2 Longitudinal differential protection

This type of unit protection could formerly only be used with pilot wires and the length of the protectable line-section was therefore limited to about 20km. The phase segregated version needs three pilot-pairs (or at least two pairs with a phantom-circuit). It has, therefore, not been frequently used. Digital relays now operate with serial interconnections between the two line terminals. Typically, a 64kbit/s channel is required to transmit the sampled current values as digital encoded numbers in a serial protocol: Pulse-code modulated standard devices (PCM 30) are available for micro-wave or optical fibre transmission. These devices have an extremely high band-width of some MBd which is normally shared between protection and other services like remote control, metering and telephone [15].

Optical fibre transmission is now also interesting for longer lines. Links of more than 100km without intermediate repeater are in service.

This opens the possibility to apply phase segregated differential protection on these lines and to use their above named advantages [5.9].

## 4.4 Back-up protection

In principle, there is no difference for back-up relaying of multi-circuit lines compared to single-circuit lines.

It has, however, to be considered that the mutual coupling effect reduces the reach of the back-up zones in case of earth-faults when the parallel line is in service while they are prolonged when the parallel line is switched off and earthed at both terminals. It is therefore often difficult to find a selective zone grading with sufficient line coverage as demonstrated in paragraph 4.2.1.1.2.

The combined impact of remote infeeds and mutual coupling normally prevent a reasonable grading of back-up zones. Local back-up philosophies are therefore recommended.

## 4.5 Automatic reclosing considerations

The standard equipment can also be used for multi-circuit lines. If single pole AR is practised, the proper phase-selection in case of double faults has to be guaranteed. This is discussed in paragraph 4.2.3. Some companies block the three-pole AR when the parallel line is out of service to avoid reclosing at a large voltage difference angle.
This can however only be considered as an exception. A supplementary synchrocheck relay is preferrable.

From Japan, two special forms of autoreclosure on multi-circuuit lines have been reported [4.32]. So called Multi-pole autoreclosure is performed on EHV lines with phase segregated unit protection: Only the faulted conductors of the parallel line are tripped and reclosed as long as at least two out of six conductors remain healthy.

Sequential reclosing is practised on resistance grounded HV-double lines: In case of multiple faults, affecting both line circuits, the tripping and reclosing of the line with a single phase-to-earth fault is delayed until the other line has been reclosed. Thus, the simultaneous outage of both line circuits shall be avoided.

## 4.6 Recent practices and trends

In the following, a summary of the replies to a CIGRE-questionnaire is given.

It was circulated in 1989 and answers were received from 49 utilities. These utilities represent 1900 lines > 250kV, 3300 lines 150 to 250kV and about 7500 lines 100 to 150kV.

### 4.6.1 Protection philosophy, state-of-the-art

The following general conclusions can be drawn from the answers:

- It seems that the utilities adhere to the classical protection concepts that have on one hand proved successful in practice since years. On the other hand, the known weak points are more or less accepted because of their low probability of occurrence (e.g. multiple faults ) or because time delayed fault clearance or non selective tripping can be accepted to a certain extent (calculable risk).
- In most cases, the protection philosophy introduced for normal single-lines is also kept, with some supplements if necessary, to protect multi-circuit lines.
- Distance relays most frequently with telecommunication in various forms of command protection (blocking or permissive schemes) are still in predominant use (87% on 400kV, 85% on 200kV and 92% on 100kV).
- Current differential protection is used to some extent with pilot wires; however, microwave or optical fibre links are the exception. Here, most applications seem to be trial installations except in Japan where the latter type of wide band communication has been widely applied for some years.
- No mention is made that digital methods or equipment would be specifically used to provide protective solutions for the problems of complex transmission networks.

### 4.6.2 Statistical Data

The percentage of multi-circuit lines of the same voltage is not uniform and varies between 0 and 100%.

The mean value is close to 50%, where the main application areas are Europe and Japan.

Parallel lines with circuits of different voltage level (e.g. 400 and 220kV) occur in some countries (DE, DK, CH) with up to 50% share in the number of multi-circuit lines.

About 45% of the replies state that mutual coupling is considered and that remedies are applied (lower zone setting to about 75 to 80% line-length or use of protection with telecommunication). The other half of the replies stated that it is not considered.

Only 37% require selective tripping and autoreclosure in case of double faults affecting different phases of parallel lines.

With reference to fault statistics, the replies to the questionnaire show that the utilies can provide information on fault rates as mean values, e.g. number of single-phase-to-earth faults per 100km and year, though it is a bit surprising that these figures vary considerably from country to country (1-Ph-E faults from 0.05 to 8.0 for 300kV and above, 0.35 to 10.4 on the 200kV level).

It is, however, difficult to get comparable figures specifically for complex networks.

Therefore, the information on double faults on multi-circuit lines is mainly based on the information of only 12 replies. It should, however, be mentioned that two countries (Belgium and France) delivered detailed statistics. They show that the fault rate of double faults on multi-circuit lines is about 10 to 20% of the comparable single-fault values stated above.

The reply from one US-utility and further available publications name higher values up to 50%. This again indicates that the local conditions (e.g. tower footing resistance) and line construction may cause a wide variance as stated also above for the single-fault statistic.

Faults between circuits of different voltage levels seem to be extremely rare (1 to 3 cases within 10 years per utility as an average. A maximum value of 10 was stated by one company, but this seems to be abnormal).

The corresponding average fault rate for intersystem faults is extremely low: 0,005 faults per 100km and year.

The following tables 4.2 to 4.7 show the summary of the CIRGE-SC 34 survey on current protection practices of 1989.

| | > 300 kV | 200 - 250 kV | 100 - 150 kV |
|---|---|---|---|
| Total number of lines (49 utilities) | 1684 | 3438 | 9277 |
| Parallel lines same voltage level | 47% | 43% | 35% |
| Parallel lines different voltage level | 8% | 13% | 5% |

**Table 4.2: Existing parallel lines**

| | > 300 kV | 200 - 250 kV | 100 - 150 kV |
|---|---|---|---|
| 1-Ph-E-Faults | 2.2<br>min. 0.05 max. 8.0 | 2.64<br>min. 0.35 max. 10.4 | 2.77<br>min. 0.4 max. 9.8 |
| 2-Ph-E-Faults | 0.16<br>min. 0.0 max. 2.0 | 0.56<br>min. 0.0 max. 2.0 | 0.65<br>min. 0.0 max. 2.7 |
| Double faults (Simultaneous faults on the two circuits of a parallel line) | 0.06<br>min. 0.0 max. 2.0 | 0.11<br>min. 0.01 max. 1.13 | 0.39<br>min. 0.0 max. 2.0 |
| Intercircuit faults (Faults between systems of different voltage level) | ca. 0.004<br>min. 0.0 max. 0.05 | ca. 0.005<br>min. 0.0 max. 0.05 | ca. 0.004<br>min. 0.0 max. 0.12 |

**Table 4.3: Fault rates (Faults per 100km and year)**

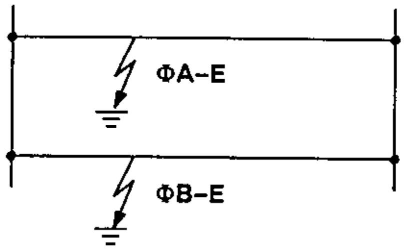
| | % of utilities use on parallel lines | | |
|---|---|---|---|
| | > 300 kV | 200 - 250 kV | 100 - 150 kV |
| Distance protection without telecommunication | 15% | 26% | 74% |
| Distance protection with telecommunication | 97% AUDP: 43% PUDP: 21% PODP: 18% BODP: 18% | 80% AUDP: 45% PUDP: 15% PODP: 20% BODP: 20% | 39% AUDP: 33% PUDP: 17% PODP: 33% BODP: 17% |
| Phase comparison protection | 24% CPCP: 40% SPCP: 60% | 9% CPCP: 30% SPCP: 70% | 3% CPCP: 100% SPCP: — |
| Differential protection | 28% PWDP: 60% FODP: 10% MWDP: 30% | 14% PWDP: 50% FODP: 33% MWDP: 17% | 19% PWDP: 66% FODP: 17% MWDP: 17% |
| Travelling wave protection | 7% | - | - |
| Sensitive earth-fault protection | 50% EP : 64% DEPZ: 22% DEPN: 14% | 57% EP : 72% DEPZ: 28% DEPN: — | 67% EP : 70% DEPZ: 30% DEPN: — |

Legend:

AUDP : Zone acceleration
PUDP : Permissive underreaching
PODP : Permissive overreaching
BODP : Blocking overreaching
CPCP : Composite current type
SPCP : Phase segregated type
PWDP : Pilot wire
FODP : Fibre optic
MWDP: Microwave
EP : Earth-fault protection, time delayed
DEPZ : Directional comparison, zero-sequence
DEPN : Directional comparison, negative sequence

**Table 4.4: Parallel lines, applied protection schemes**

- Is phase selective tripping and single pole AR required in the following case?




| | | |
|---|---|---|
| Yes | : | 37% |
| No | : | 46% |
| No statement | : | 27% |

- If "Yes", what are the applied measures?

| | | |
|---|---|---|
| - Phase segregated unit protection | : | 6% |
| - Phase segregated non-unit protection | : | 4% |
| - Distance protection with AR-controlled zone reach | : | 10% |
| - Use a teleprotection scheme and accept 3-phase tripping of both lines for near-line-end faults | : | 10% |
| - No statement | : | 70% |

**Table 4.5: Parallel line protection, simultaneous faults**

- Is mutual coupling considered ?

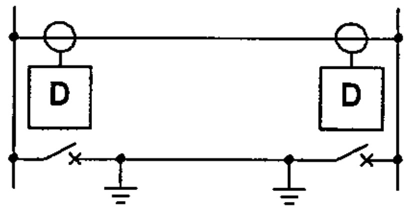
| | | | |
|---|---|---|---|
| Yes | : | 45% | of utilities |
| No | : | 49% | |
| No statement | : | 6% | |

- Are measures applied to avoid the adverse effects of mutual coupling ?

| | | |
|---|---|---|
| – Parallel line compensation | | |
| of the distance protection | : | 12% |
| of the fault locator only | : | 33% |
| – Application of a phase-segregated teleprotection scheme | : | 4% |
| – Using directional earth fault-relaying (negative – or zero – sequence) | : | 10% |
| – Use a teleprotection scheme and accept 3-phase tripping of both lines for near-line-end faults | : | 10% |
| – No statement | : | 70% |

**Table 4.6: Protection of parallel lines, mutual coupling effect**

- How is overreach prevented in the case of a switched-off and earthed parallel line?




| | | |
|---|---|---|
| – by mutual compensation ( only possible with line side CTs.) | : | 4% |
| – by reduced zone setting | : | 30% |
| – by a teleprotection scheme | : | 28% |
| – by <u>not</u> earthing at <u>both</u> line ends | : | 4% |
| – no answer | : | 34% |

- The reduced zone setting is:

| | | |
|---|---|---|
| 50% | 70% | 80% |
| min. | average | max. |

**Table 4.7: Parallel line protection, distance zone grading**

## 4.7 Appendices

**Appendix 1: Zero-sequence coupling impedance calculation**

For overhead lines without earth conductors, the zero sequence mutual coupling reactance $X_{0M}$ can be estimated by the following formula:

$$(X_0 - X_L) - X_{0M} = j\ 2\ \pi \times f \times 4.6 \times 10^{-4} \times \log\left(\frac{\Delta}{D}\right)$$

f: Network frequency

$X_{0M}$: Mutual coupling reactance

$X_L$: Line positive sequence reactance

$X_0$: Line zero sequence reactance

D: Geometric mean distance between conductors of the same line

$$D = \sqrt[3]{d1 \cdot d2 \cdot d3}$$

Δ: Geometric mean distance between one conductor and conductors of the other line

$$\Delta = \sqrt[9]{Daa' \cdot Dab' \cdot Dac' \cdot Dba' \cdot Dbb' \cdot Dbc' \cdot Dca' \cdot Dcb' \cdot Dcc'}$$

For lines with earth wires a simple formula does not exist but a specialized program must be used to compute the zero sequence mutual impedance, or the real values have to be measured.

Example:

Approximate values of $k_{0M} = \dfrac{X_{0M}}{3 \cdot X_L}$ are given in the following table :

$X_L$ line positive sequence line impedance: 0.41 Ω/km

$X_0$ zero sequence line impedance: 1.23 Ω/km

d distance between the parallel lines in meter

| d | 5 | 7.5 | 10 | 15 | 20 | 30 | 50 | 100 | 200 | 400 | 600 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $k_{0M}$ | 0.71 | 0.64 | 0.61 | 0.54 | 0.51 | 0.45 | 0.4 | 0.29 | 0.18 | 0.1 | 0.06 |

**Table 4.8 Approximate values of $K_{0M}$ (50Hz)**

Appendix 2: Typical zero-sequence coupling impedance charts

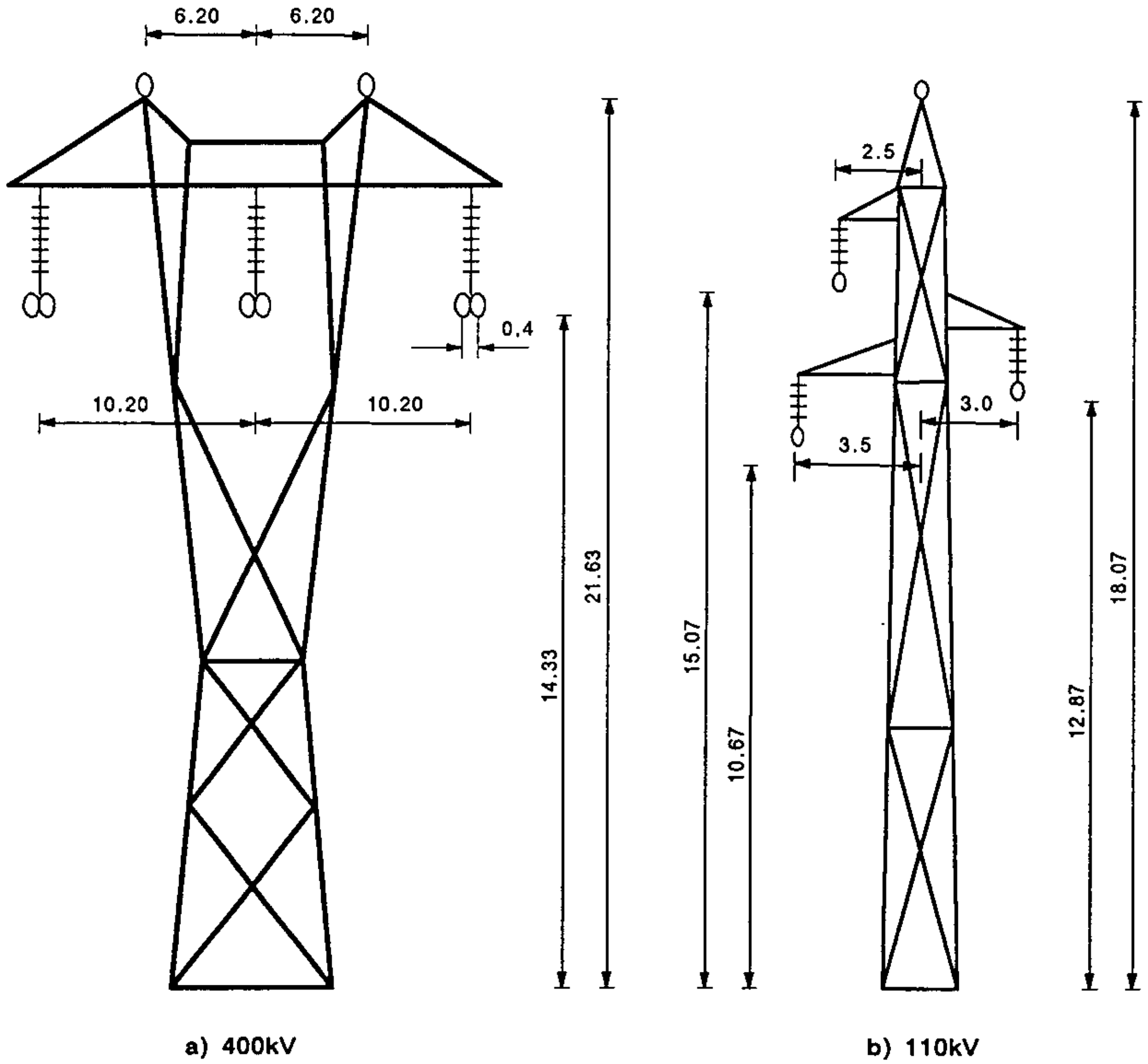



Fig. 4.32: Typical tower configurations

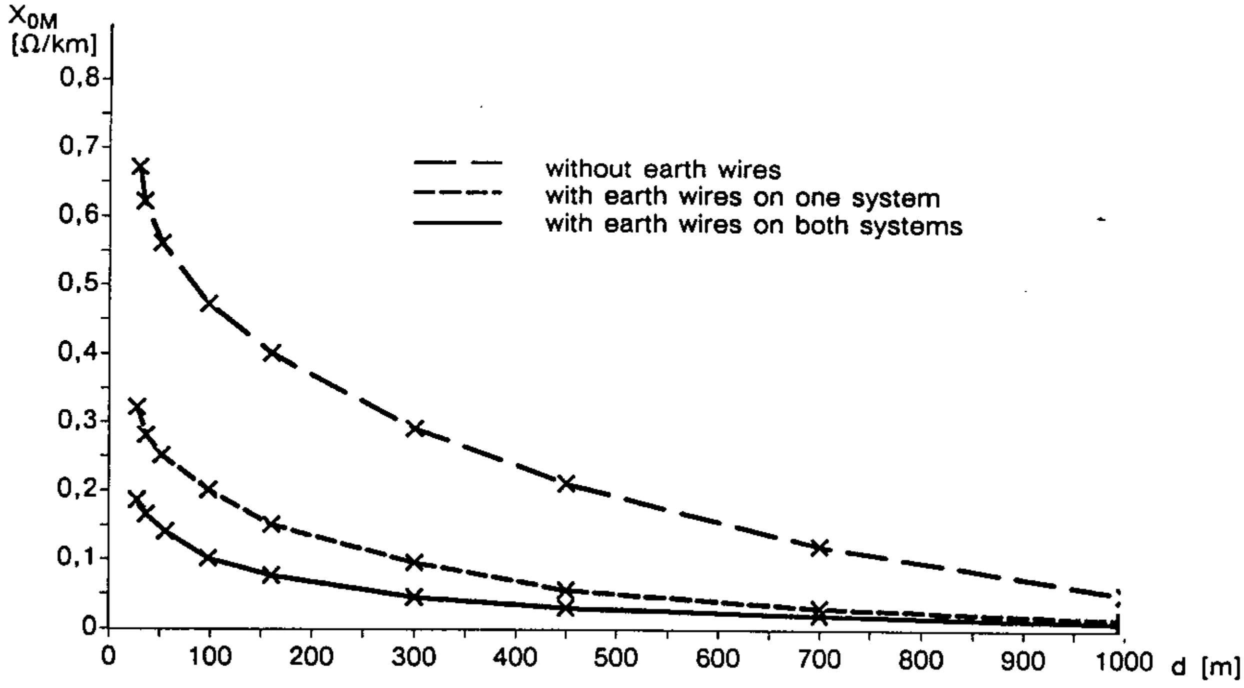



Fig. 4.33: Typical mutual reactances for 400 kV lines, ρ = 100 Ωm (50Hz values)

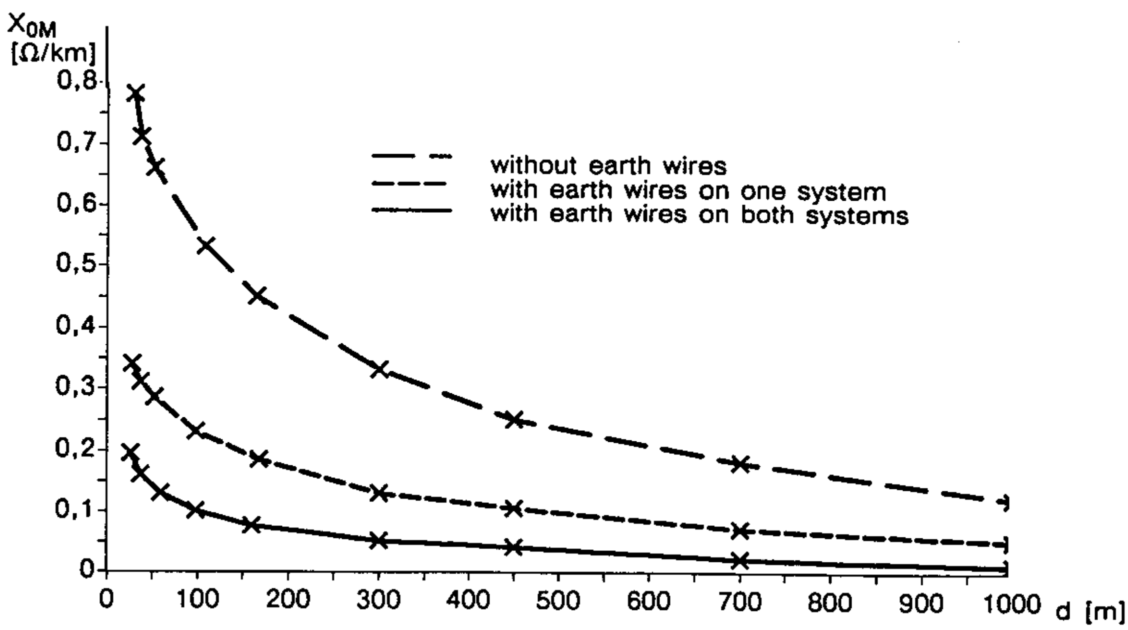



Fig. 4.34: Typical mutual reactances for 400 kV lines, ρ = 300 Ωm (50Hz values)

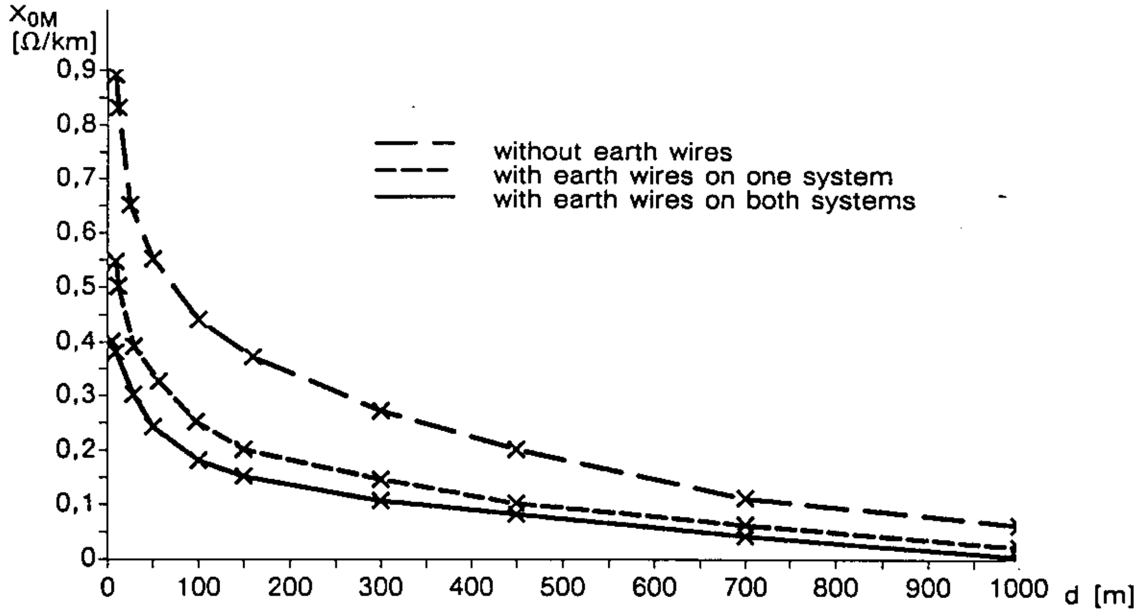



**Fig. 4.35: Typical mutual reactances for 110 kV lines, ρ = 100 Ωm (50Hz values)**

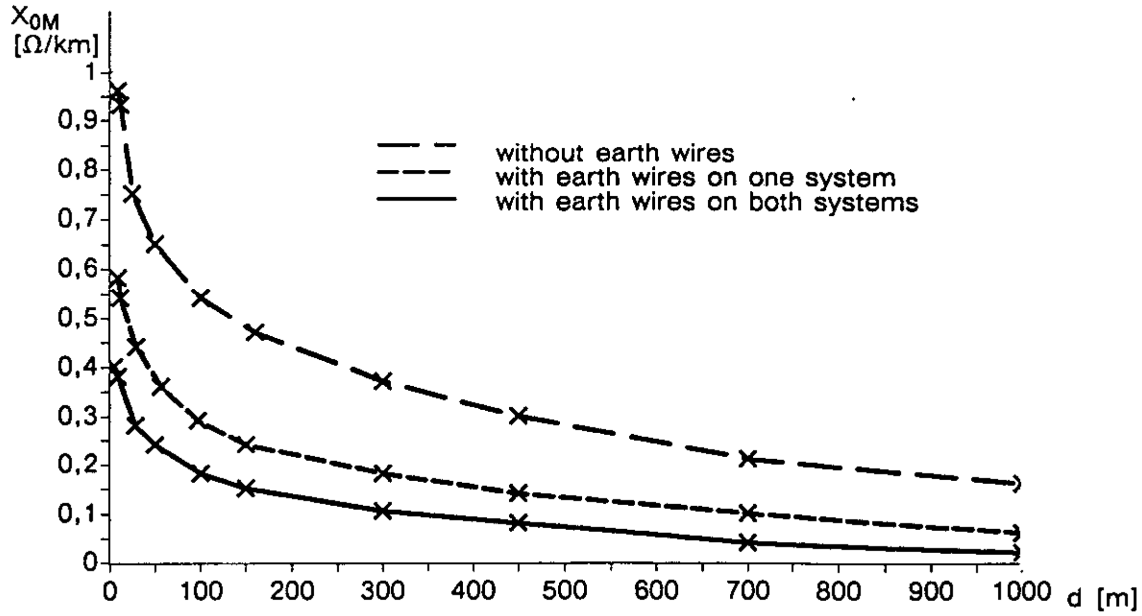



**Fig. 4.36: Typical mutual reacctances for 110 kV lines, ρ = 300 Ωm (50Hz values)**

Appendix 3: Measurement of line impedances for the setting of distance protection and fault locators

## 1) Set-up of the measuring circuit

### 1.1) Schematic diagram

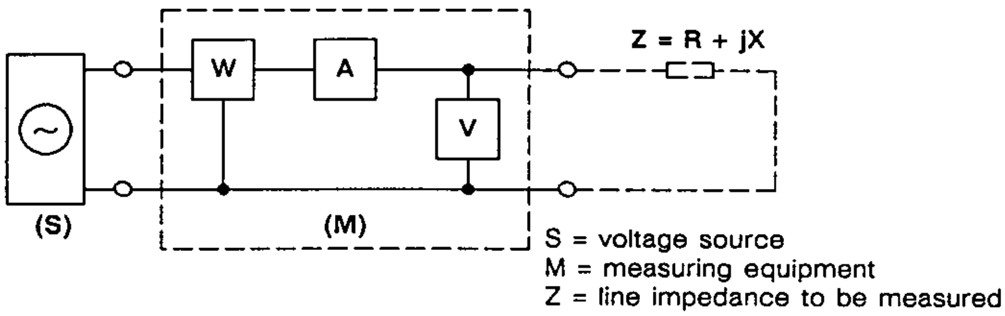



Fig. 4.37

### 1.2) (S): LV supply at 50 or 60Hz system frequency

Normally a source voltage of 220V is used to comply with the measuring equipment ratings.

**Note:** There are two possible cases:

a) The supply (S) can be an isolated (transformer) and, if necessary, regulated (stabilized) and adjustable.
In this case, it will be necessary to ensure that the supply has a harmonic content of less than 2% for the harmonics H3 and H5 and of less than 1% for higher harmonics.

b) Another voltage source is the substation auxiliary supply. Generally, this supply is 220V/380V three-phase with earthed neutral.
In this case, as the supply is obtained from the HV network, it generally satisfies the conditions for low harmonic contents.

### 1.3) (M): Measuring equipment

- The "voltage" rating of the most appropriate voltmeter and wattmeter is generally 250V, 300V or 500V.

  The "current" rating of the ammeter and wattmeter should generally be matched to 2.5A, 5A, 10A. They are then suitable for medium or long lines.

  **Note:** It is necessary to make a preliminary calculation of the order of magnitude of the line impedances to be measured in order to match the supply (S) voltage to the ratings of the measuring equipment.

- The accuracy class of the measuring equipment must be 0.5%. This accuracy must have been checked recently in a laboratory where reference equipment is available.

- Impedance measurement $Z = R + j \cdot X$,
  where $X = L \cdot \omega$ and $\omega = 2 \cdot \pi \cdot f$;
  f is the network frequency (50 or 60Hz).

Reading of the measuring values:

I in Amps
V in Volts
P in Watts.

**Calculation of Z, R, X and $\varphi$**

Modulus of Z: $|Z| = V/I$
$\varphi = \arccos P/(V \cdot I)$
$X = Z \cdot \sin \varphi$
$R = Z \cdot \cos \varphi = V/I \times P/(V \times I) = P/I^2$
Verification: $Z^2 = R^2 + X^2$

**2) Line Impedance measurements**

**2.1)** The complete measurement of a three-phase line comprises seven distinct measurements:

Three ph-ph measurements: $Z_{ab}$, $Z_{bc}$, $Z_{ca}$

Three phase-earth measurements: $Z_{aE}$, $Z_{bE}$, $Z_{cE}$

One zero sequence measurement: $Z_0$.

**Note:** If the line structure is dissymmetric and not transposed, there will be differences between the three measurements for the same group.

E.g.:

- For a horizontal bundle line, we will obtain: $Z_{ab} \approx Z_{bc} < Z_{ca}$ (the difference can reach 8 to 10%) and $Z_{aE} \approx Z_{bE} \approx Z_{cE}$
- For a line in which the conductor layout is similar to an equilateral triangle, we obtain $Z_{ab} \approx Z_{bc} \approx Z_{ca}$ and $Z_a > Z_b \approx Z_c$
- For a flag conductor line, dissymmetry will be obtained both for $Z_{ph\text{-}ph}$ and $Z_{ph\text{-}E}$

The presence of one or two steel-aluminium or steel guard-wires will modify the measured impedances and also the dissymmetry.

**2.2)** These measurements are performed to determine the average values of $Z_{ph\text{-}ph}$ and $Z_{ph\text{-}E}$.The values are then used to deduce the positive- and zero-sequence line impedances:

**2.2.1)** Positive sequence impedance per phase:

$Z_1 = (Z_{ab} + Z_{bc} + Z_{ca})/2 \times 3$

The zero sequence impedance $Z_0$ is determined separately by a single measurement:

$Z_0 = V_0/I_0 = 3V_0/I_R$; $I_R$ = residual current

**Note:** For a dissymmetric non-transposed line, with or without guard wires, it is also advisable, in addition to measuring $I_R$, to check the current values for the three phases a, b, and c and to evaluate any dispersion with respect to $I_R/3$.

**2.2.2)** The phase-to-earth impedance measurement $Z_{ph\text{-}E}$ will be used for a verification check, by comparing the average measured value $Z_{ph\text{-}E} = (Z_{aE} + Z_{bE} + Z_{cE})/3$ and the theoretical value $Z_{ph\text{-}E} = (2Z_1 + Z_0)/3$.

The difference should not exceed **2%**.

2.2.3) Calculation of the dissymmetry

With respect to the average values calculated above, the differences

$Z_{ab}/2 - Z_1$, $Z_{bc}/2 - Z_1$, $Z_{ca}/2 - Z_1$

can be determined to estimate the protection measurement deviations and in particular the fault locator measurement deviations for different fault-types.

2.2.4) Kilometric line impedances

If the impedances calculated above are divided by the exact length of the line in km, the kilometric line parameters are obtained:

$Z_{1/km} = R_1 + j \cdot X_1$ Argument $\varphi_1$ in degrees

$Z_{0/km} = R_0 + j \cdot X_0$ Argument $\varphi_0$ in degrees

$Z_{ph-E/km} = R_{ph-E} + j \cdot X_{ph-E}$ Argument $\varphi_{ph-E}$ in degrees

For a double line or a parallel line, it will also be necessary to calculate the mutual kilometric impedance (see section 4.1.2).

$Z_{0M/km} = R_{0M} + j \cdot X_{0M}$ Argument $\varphi_{0M}$ in degrees;

The values found above can be compared with the values obtained from a theoretical calculation on basis of the line geometry.

The validity of the measured values can further be estimated by comparing them with the known typical orders of magnitude:

For a HV line with a small cross-section single conductor per phase and without guard conductor, the results will be approximately (at 50Hz):

$X_{1/km}$ 0.4 to 0.45 Ohm/phase Argument $\varphi_1 = 50$ to 75°

$X_{0/km}$ 0.9 to 1.4 Ohm/phase Argument $\varphi_0 = 70$ to 75°

$X_0/X_1 \approx 3$

For an EHV line with four large cross-section conductors per phase, and without earth wires, the results will be approximately (at 50Hz):

$X_{1/km}$ 0.27 to 0.32 Ohm/phase Argument $\varphi_1 = 80$ to 85°

$X_{0/km}$ 1.0 to 1.4 Ohm/phase Argument $\varphi_0 \approx 75°$

$X_0/X_1 \approx 4$

For the same line, with two aluminium-steel earth wires, we find approximately the same value for $Z_1$ and $\varphi_1$, but a value of $Z_0 = 0.7$ to 0.8 Ohm/phase. This demonstrates that the effect of the earth wires decreases the zero sequence impedance by almost half, resulting in:

$X_0/X_1 \approx 2$ to 2.5

## 3) Connection diagrams

### 3.1) Measurement of $Z_{ab}$ ($Z_{bc}$, $Z_{ca}$)

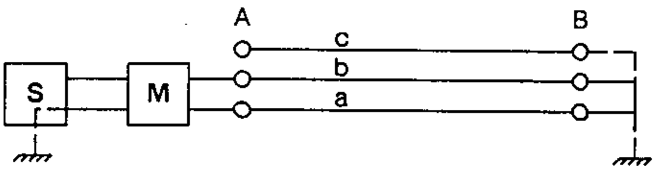



Fig. 4.38

- **Important Note:**

  The supplementary short-circuit of phase c with phases a and b, or not, makes no difference. However, the supplementary short-circuit to earth at B can only be used if supply S is isolated from earth. With an earthed supply S a phase-to-phase short-circuit <u>without</u> earth must be used at B. This means that in this case, the short-circuit at B cannot be made through the line earthing-switch.

### 3.2) Measurement of $Z_0$

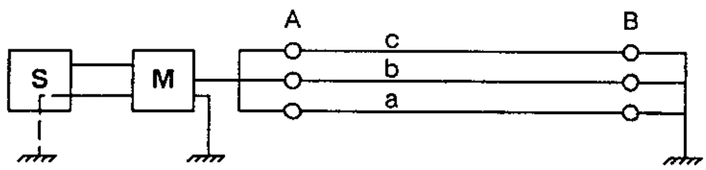



Fig. 4.39

- At B, the three conductors a, b, c must be short-circuited and connected to the substation high voltage earth; the short-circuit can be made by the earthing-switch.
- At A, it will also be necessary to use a link to a substation high voltage earth conductor in all cases, whether the supply S is isolated or not.

### 3.3) Measurement of $Z_{aE}$ ($Z_{bE}$, $Z_{cE}$)

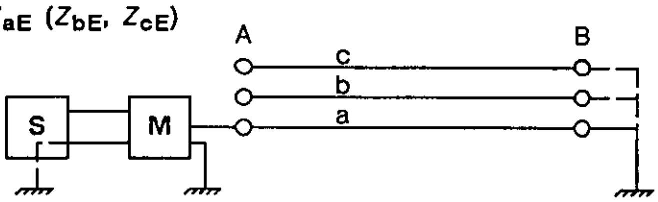



Fig. 4.40

At B, any supplementary short-circuits of phases b and c will have no effect on the measurement.

At A, the same remark applies as above.

### 3.4) General Remark

All the line links must be made with low resistance conductors. Earthing rods with jaws connecting them to the line and large cross-section flexible cables can be used.

4) **Double circuit line**

**4.1)** It is absolutely necessary that the parallel line is completely isolated at both ends; the zero sequence impedance measurement at the other line would otherwise be incorrect.

**4.2)** Measurement of the mutual zero sequence impedance $Z_{0M}$

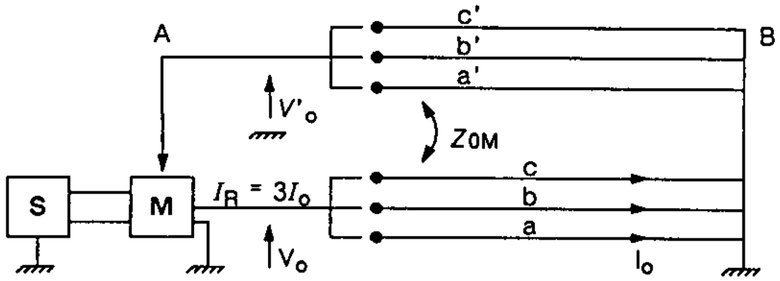



**Fig. 4.41**

The same connection is used for one line as for the measurement of $Z_0$ (see 3.2).

At B, the parallel line is short-circuited and the three phases are earthed.

At A, the measurement of $V'_0$ is made between the three phases connected together and earth.

$$Z_{0M} = V'_0/I_0 = 3V'_0/I_R = R_{0M} + j \cdot X_{0M}$$

5) **Remarks on the validity of line characteristic data measured with a low voltage source**

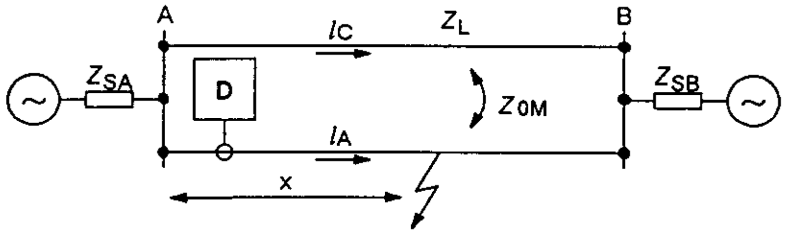
To ensure that the measurements are valid, it will be necessary to check that there is no interference from an energized or on-load adjacent line, or any other source, such as of a nearby electrified railway line. It has to be verified that the open line (without infeed) is free of interference voltages. It is also possible to check that there is no noise current at the short-circuited line.

6) **Measuring in substations – safety conditions**

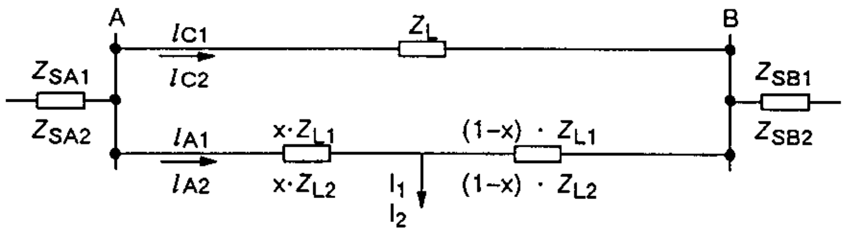
- With the line isolated, the busbar isolating switches are to be locked in the open position so that an accidental operation of the circuit breaker is ineffective.
- The measurement or short-circuit connections are to be prepared with closed earth isolating switches.
  After opening the earth isolating switches and providing power from supply (S), readings are to be made on the equipment without touching the conductors.
- These measurement operations are forbidden if there is any risk of a storm arising on the line path.
- When inductive voltage reducers are used, the secondary fuses are to be disconnected to avoid any risks of voltage return by substation circuitry.
- The measurements shall only be performed by authorized qualified personnel completely familiar with substation installations and the safety regulations for working at HV-lines.

**Attention: There is danger of life by possibly induced high voltage!**

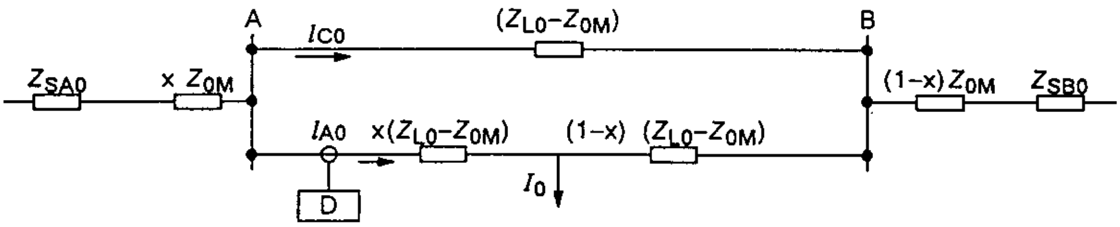
Appendix 4: Earth-faults on parallel lines
Distance measurement without mutual compensation




a) Single line diagram




b) Positive and negative sequence network diagram




c) Zero sequence network diagram

Fig. 4.42

For a single phase to earth fault: $I_1 = I_2 = I_0$

$$I_{A1} = \frac{(2-x)Z_{SB1} + (1-x)(Z_{SA1} + Z_{L1})}{2(Z_{SA1} + Z_{SB1}) + Z_{L1}} \; I_1 \qquad (1)$$

$$I_{A2} = I_{A1}$$

$$I_{A0} = \frac{(2-x)Z_{SB0} + (1-x)(Z_{SA0} + Z_{L0} + Z_{0M})}{2(Z_{SA0} + Z_{SB0}) + Z_{L0} + Z_{0M}} \; I_0 \qquad (2)$$

**Calculation example:** Parallel line, single infeed

$Z_{SB1} = Z_{SB2} = Z_{SB0} = \infty$

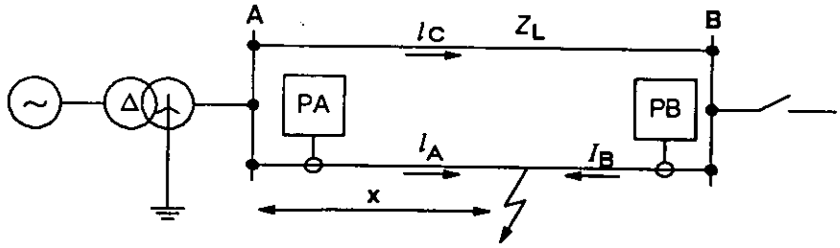



Fig. 4.43

Phase currents: $I_{LA} = I_{A1} + I_{A2} + I_{A0}$ $\quad$ $I_{LB} = I_{B1} + I_{B2} + I_{B0}$

Residual currents: $I_{RA} = 3\, I_{A0}$ $\quad$ $I_{RB} = 3\, I_{B0}$

$$k_0 = \frac{Z_{L0} - Z_{L1}}{3\, Z_{L1}};\ k_{0M} = \frac{Z_{0M}}{3\, Z_{L1}}$$

(1) and (2) $\Rightarrow \dfrac{I_{C0}}{I_{A0}} = \dfrac{x}{2-x}$

For relay PA the measured impedance is $Z_A$

$$Z_A = \frac{V_A}{I_A} = x\, Z_{L1} \frac{I_{LA} + k_0\, I_{RA} + k_{0M}\, I_{RC}}{I_{LA} + k_0\, I_{RA}}$$

$$Z_A = x\, Z_{L1} \left(1 + \underbrace{\frac{k_{0M} \dfrac{x}{2-x}}{1 + k_0}}_{\text{Measuring error}}\right)$$

For relay PB: $I_{B0} = -\, I_{C0}$

The measured impedance is $Z_B$

$$Z_B = \frac{V_A}{I_A} = (l-x)\, Z_L \left(1 - \underbrace{\frac{k_{0M}}{1 + k_0}}_{\text{Measuring error}}\right)$$

Voltage and current at the measuring point:

$$V_A = 2(I_{A1} \cdot Z_{L1}) = Z_{L0}\, I_{A0} + Z_{0M}\, I_{C0}$$

$$I_A = 2I_{A1} + I_{A0}$$

The figure 4.44 below shows the protection reach for a parallel line with the characteristic data $k_0 = 0.66$ and $k_{0M} = 0.4$.

It can be seen that protection P(A) experiences an underreach that increases with the fault distance and amounts to a maximum of 25% for a fault at the line end in B.

Protection P(B) overreaches with a constant amount of 25%.

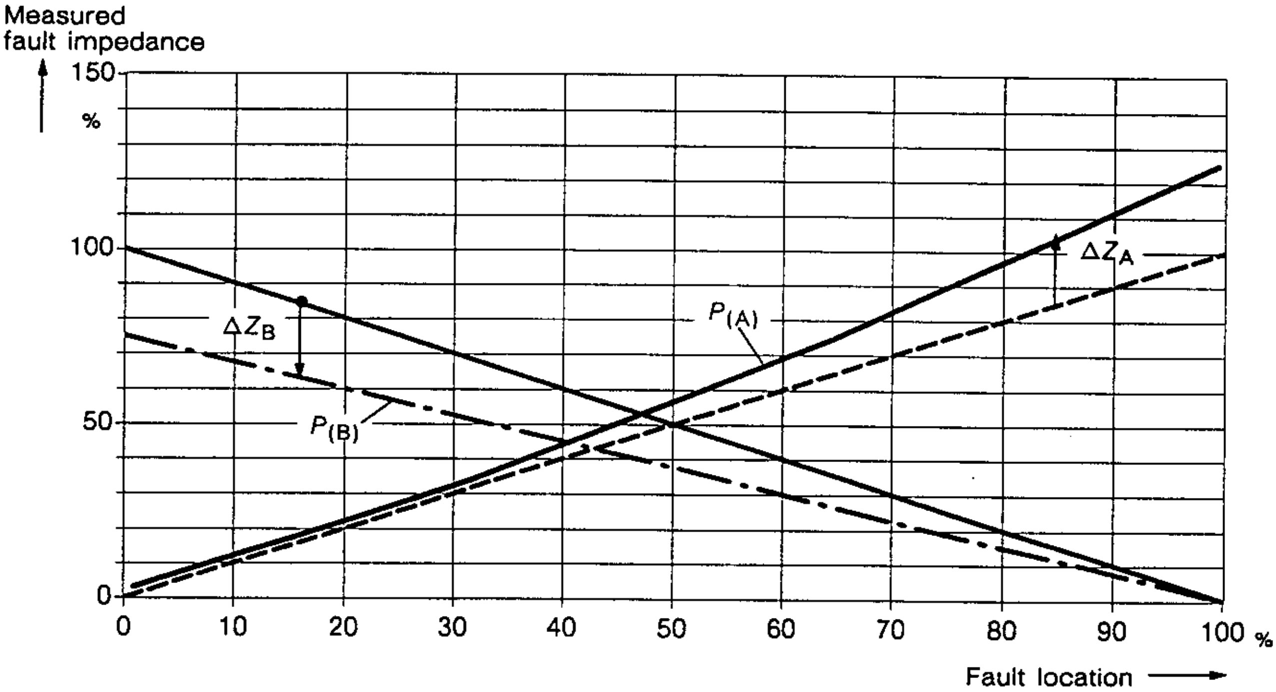



**Fig. 4.44: Distance protection <u>without</u> mutual compensation**

**Notes:** A commonly practised setting for the 1st zone is 80% (without signalling scheme or in permissive underreach schemes). Due to the fact that one protection is underreaching and the other one is overreaching there is always an overlapping that allows a fast trip at least at one end.

The overreach of P(B) is not a problem because when it occurs for external faults the fault must lie near B on the parallel line and the fault current must flow in reverse direction in B, i.e. the protection anyway blocks as the fault is seen in reverse direction.

In a permissive overreach scheme or in a blocking scheme the Z1 coverage must always overreach the line impedance and must take into account the reach reduction. In this case, the P(A) zone 1 has to be set to about 150% of the single-line impedance in order to keep a safety margin of 20%.

Consequently, it is normally not necessary to compensate for the effect of the zero sequence mutual impedance in a distance relay, but it is necessary to provide this compensation in a fault locator.

## Appendix 5: Earth-faults on parallel lines
### Distance measurement with mutual compensation

Although the distance protection with mutual compensation measures the correct distance-to-fault on the faulted line it may not operate correctly on the healthy parallel line.

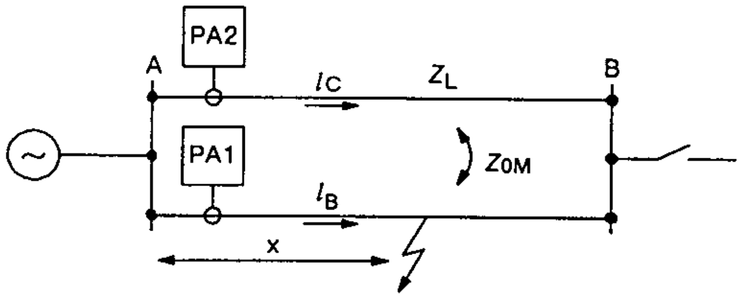



Fig. 4.45

Impedance measured by relay PA1:

$$Z_{PA1} = \frac{V_A}{I_B + k_0 \cdot I_{RB} + k_{0M} \cdot I_{RC}} \quad (1)$$

$I_B$, $I_C$ = phase currents
$I_{RB}$, $I_{RC}$ = residual currents
$V_A$ = phase-to-earth voltage

Impedance measured by relay PA2:

$$Z_{PA2} = \frac{V_A}{I_C + k_0 \cdot I_{RC} + k_{0M} \cdot I_{RB}} \quad (2)$$

(1) and (2) $\Rightarrow Z_{RA2} = Z_{RA1} \cdot \dfrac{I_B + k_0 \cdot I_{RB} + k_{0M} \cdot I_{RC}}{I_C + k_0 \cdot I_{RC} + k_{0M} \cdot I_{RB}}$

Mutual compensation being exact:

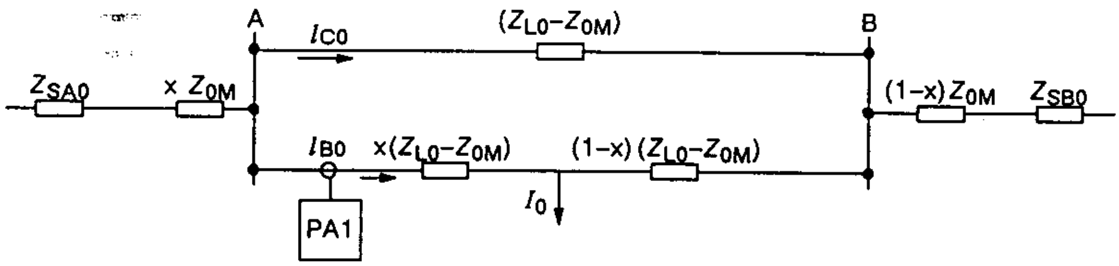



Fig. 4.46

$\Rightarrow Z_{RA2} = x\ Z_L \cdot A$ with $A = \dfrac{I_B + k_0 \cdot I_{RB} + k_{0M} \cdot I_{RC}}{I_C + k_0 \cdot I_{RC} + k_{0M} \cdot I_{RB}}$

Without source in B

$I_C = I_{RC}$
$I_B = I_{RB}$
$I_C/I_B = x/(2-x)$

$$\Longrightarrow \quad A = \frac{(1 + k_0) + k_{0M}\,\frac{x}{2-x}}{(1 + k_0)\,\frac{x}{2-x} + k_{0M}}$$

If $n \cdot Z_L$ is the 1st zone setting of PA1 and PA2, non selectivity of PA2 will be experienced under the condition:

$Z_{PA2} \leq n \cdot Z_L$, that means $x \cdot Z_L \cdot A \leq n \cdot Z_L$ or $x \cdot A \leq n$

This condition delivers the following equation:

$$x^2(1 + k_0 - k_{0M}) - x \cdot [(1 + k_0)(2 - n) + n \cdot k_{0M}] + 2 \cdot n \cdot k_{0M} \geq 0 \qquad (6)$$

Example:

$k_0 = 0.66; \qquad k_{0M} = 0.4$

1st zone setting 80% of $Z_L$, i.e. $n = 0.8$

$$\Rightarrow 1.26\, x^2 - 2.312\, x + 0.64 \geq 0 \qquad (7)$$

Solutions are:

$x' = 0.34$

$x'' = 1.495$ (not relevant)

The non-selectivity of PA2 exists for fault locations in the range of

$0 < x < 0.34$

To avoid false tripping of the healthy line, countermeasures must be taken. The most common one is to compare the magnitude of the zero sequence currents of both lines and to perform the compensation only in that line where the zero sequence current is higher by a certain amount compared with that of the parallel line.

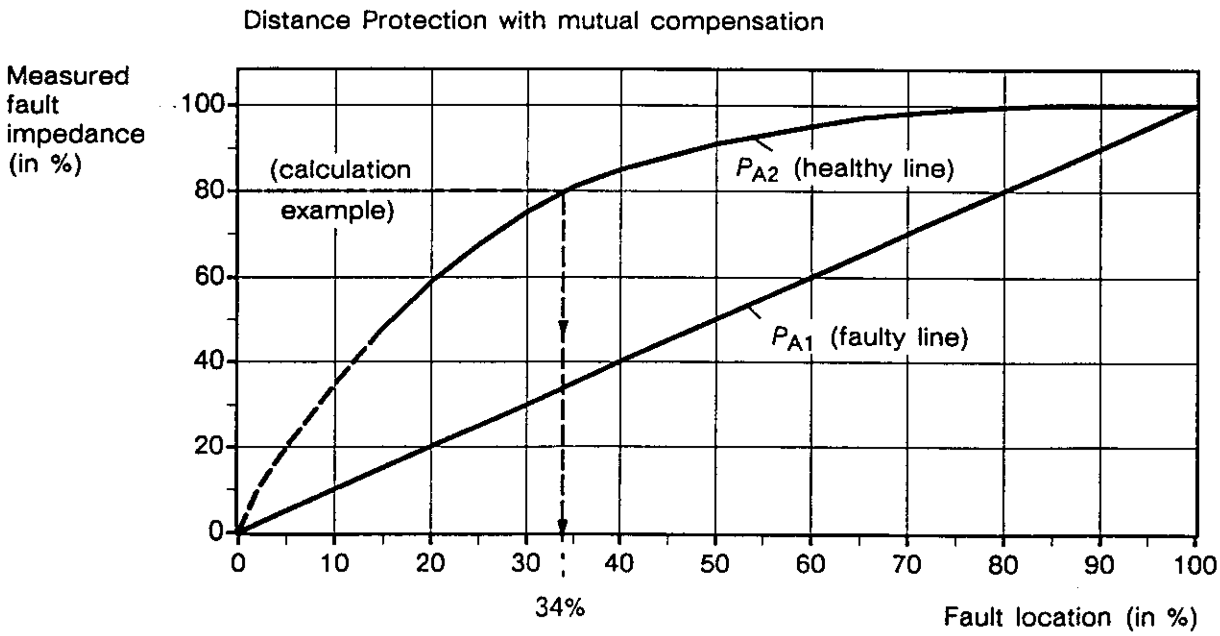



**Fig.4.47: Distance protection with mutual compensation, measured fault impedances**

## Appendix 6: Fault location on parallel lines

**1) Parallel lines ending at the same substation**

As mentioned above it is necessary to compensate the zero sequence mutual coupling impedance to obtain accurate measurement of the distance from the substation to the fault.

**2) Partly parallel lines ending in different substations:**

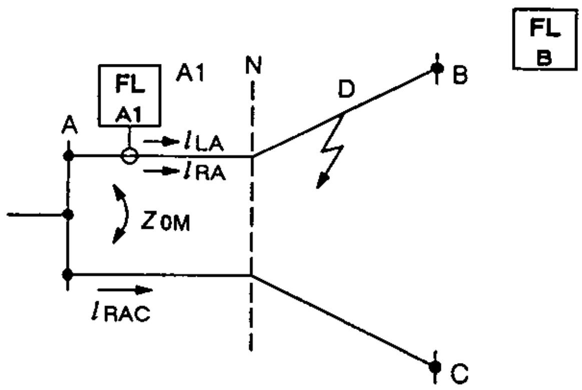



Fig. 4.48

**2.1) Lines with power generation at each substation**

The lines run parallel from substation A to point N.

Fault locators must be installed at each terminal. The fault locators at substation A are provided with mutual compensation. Their measured distance-to-fault is accurate for faults up to point N.

For a fault on line AB, if the distance display of the fault locator (FL) A1 is greater than the distance AN, only the display of fault locator FL B is accurate. On the other hand if the FL A1 display is less than the distance AN, the distance displayed at A1 is correct and the display of FL B should not be read.

**2.2) Lines without power generation at the remote terminal in B or C**

Two FLs must be installed in A at each feeder, one with mutual compensation, and the other one without mutual compensation.

For example, no generation in B:

We call:
Lc the display of the fault locator with compensation
L the display of the fault locator without compensation.

If Lc is less than the distance AN ($d_{AN}$), Lc is the correct fault location.
If Lc is greater than $d_{AN}$ the distance to fault is given by the formula: $D = L + d_{AN} \cdot (1 - L/Lc)$

This can be developed as follows:

$$L = \frac{V_A}{z(I_{LA} + k_0\, I_{RA})} = \frac{d_{AN}\, z(I_{LA} + k_0\, I_{RA} + k_{0M}\, I_{RAC}) + d_{ND}\, z(I_{LA} + k_0\, I_{RA})}{z \cdot (I_{LA} + k_0\, I_{RA})}$$

With
- $z$: line positive sequence impedance (Ω/km)
- $d_{AN}$: distance from terminal A to point N
- $d_{ND}$: distance from point N to the fault (D).
- $V_A$: Ph–E–voltage in A
- $I_{LA}$: Line current in A
- $I_{RA}$: Residual current in line A–B at A
- $I_{RAC}$: Residual current in line A–C

$$L_C = \frac{V_A}{z(I_{LA} + k_0\, I_{RA} + k_{0M}\, I_{RAC})} = \frac{d_{AN}\, z(I_{LA} + k_0\, I_{RA} + k_{0M}\, I_{RAC}) + d_{ND}\, z(I_{LA} + k_0\, I_{RA})}{z \cdot (I_{LA} + k_0\, I_{RA} + k_{0M} \cdot I_{RAC})}$$

If we write

$$A = \frac{I_{LA} + k_0\, I_{RA} + k_{0M}\, I_{RAC}}{I_{LA} + k_0\, I_{RA}}$$

we get: $L = d_{AN} \cdot A + d_{ND}$

$L_C = d_{AN} + d_{ND}/A$

$\Rightarrow A = L/L_C$

Then:

$$\boxed{d_{ND} = L - d_{AN}\, \frac{L}{L_C}}$$

# 5 Protection of Multiterminal and Tapped Lines

## 5.1 Introduction

**Multi-terminal lines** are lines having three or more terminals with substantial generation behind each.

**Tapped lines** are lines having one or more terminals with substantial generation behind them and taps feeding only load. The taps do not have sufficient current feed-back to operate relays.

The feed-back at a tap will only appear in the zero-sequence system when an earthed transformer is connected to a line without generation behind it. The tap may in this case be treated like an infeed-terminal for the layout of the earth-fault protection.

A terminal may part-time be without or only with weak back-feed when generation is switched-off. In this case the terminal has to be treated like a tap, e.g. by a weak-infeed supplement to the line protection.

### 5.1.1 Application range

The main reasons for applying these network configurations are cost saving or environmental protection. By connecting a branch or transformer directly to the high voltage line, no additional substation and circuit breakers are required.

On the other hand protection problems may be introduced, especially when distance protection is used: high apparent impedances may be measured due to intermediate infeed, or, in the case of tapped lines, discrimination between line and transformer faults may be difficult.

Therefore, a close cooperation between system designers and protection engineers in an early stage is advised.

System design may also lead to special requirements for the protection scheme with respect to fault clearing times, selectivity , etc.

For example, in the neighbourhood of power stations fault clearing times longer than e.g. 0.2s may be intolerable because of the risk of instability.

A relaying scheme without telecommunication is therefore not an appropriate solution in this case: sequential tripping may lead to unacceptable long fault clearing times.

The recent practice shows that there is no general tendency to apply these network-configurations more often on all voltage levels. However, in 110/150kV-networks, tapped lines are becoming more and more wide-spread.

### 5.1.2 Most frequent network configurations

The typical multiterminal line (MTL-)configurations are (S: Strong source; W: Weak source)

MTL 1

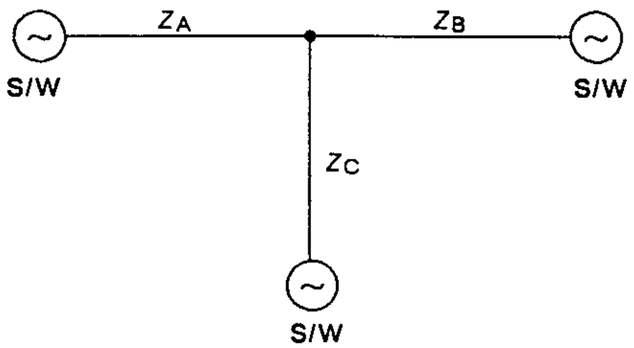



Fig. 5.1: Equal legs

MTL 2

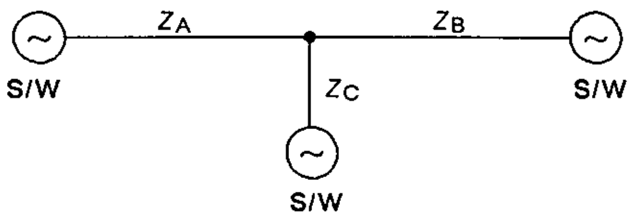



Fig. 5.2: One short leg

MTL 3

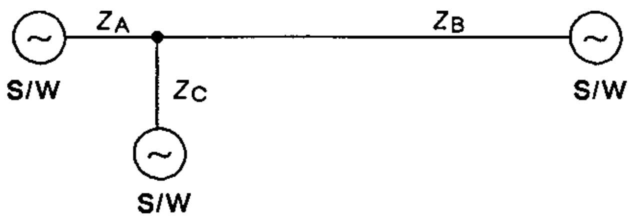



Fig. 5.3: Two short legs

MTL 4

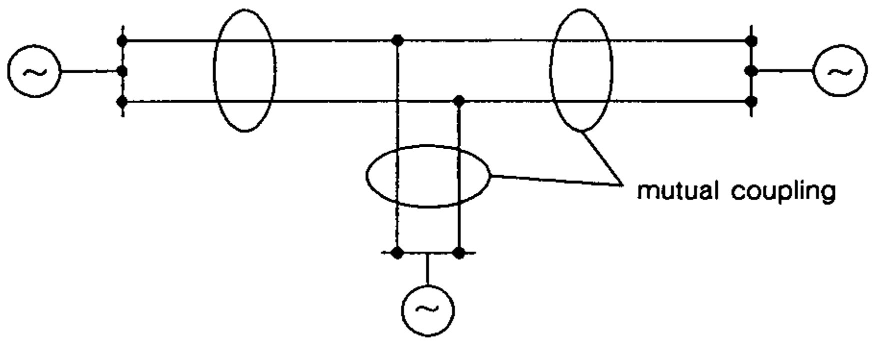



Fig. 5.4: Mutually coupled MTL

The most typical tapped line (TL-)configurations are:

TL 1

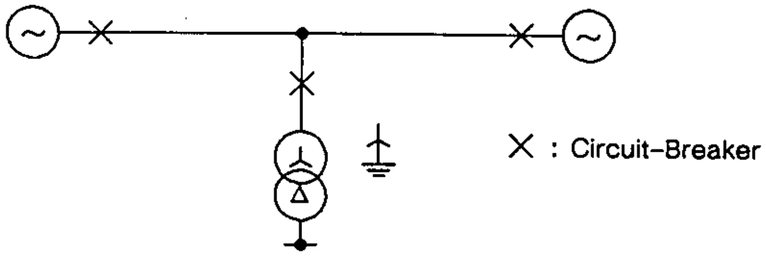



Fig. 5.5: Tap with earthed transformer

TL 2

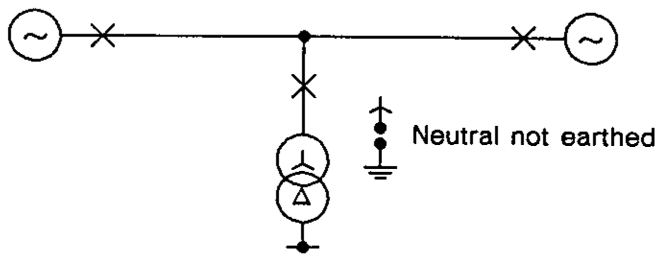



Fig. 5.6: Tap with non-earthed transformer ($Z_0$-tap infinite)

Less frequent are:

TL 3

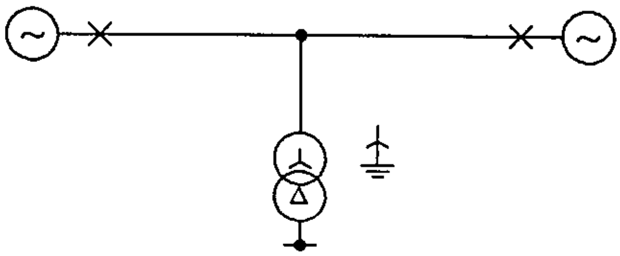


Fig. 5.7: Tap without circuit breaker and earthed transformer

TL 4

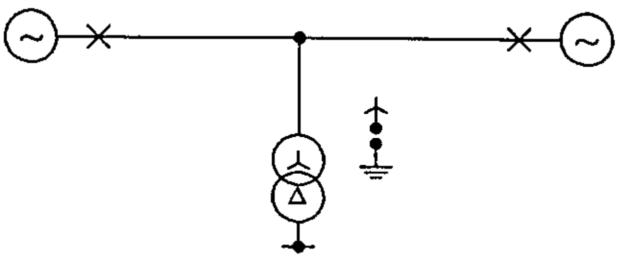


Fig. 5.8: Tap without circuit breaker and non-earthed transformer ($Z_0$-tap infinite)

TL 5

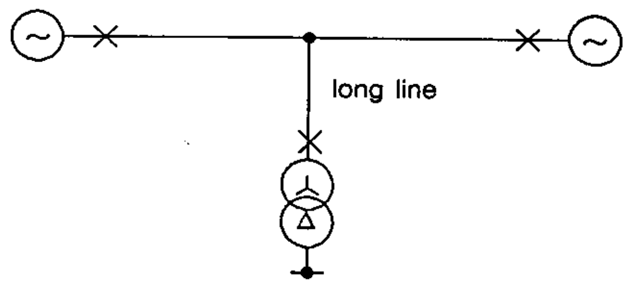



Fig. 5.9: Tap with long line

The number of taps per line vary between 1 and more than 10.

Tapped lines with backfeed (TLB) may be considered as special cases of multi-terminal lines especially when the back-feed fault current is too small to activate normal line protection

TLB

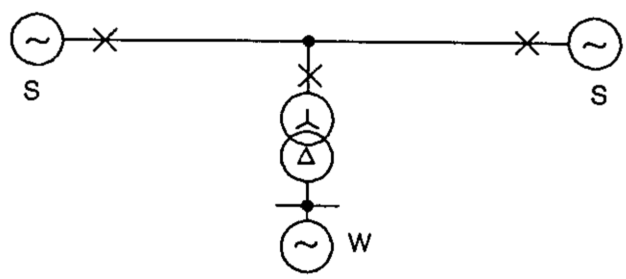



Fig. 5.10: Tap with weak back-feed

Also here the number of taps may vary between 1 and more than 10. Taps with backfeed are in general industrial or hydro plants directly connected to a HV-line.

## 5.2 Protection problems encountered

The main difficulties with distance relays are the different line lengths to the tap point and the different source impedances behind the terminals. The infeed problem makes it almost impossible to cover the major part of the line by zone 1 without being unselective with respect to adjacent lines.

### 5.2.1 Multi-terminal lines

Take for example the following three-terminal line:

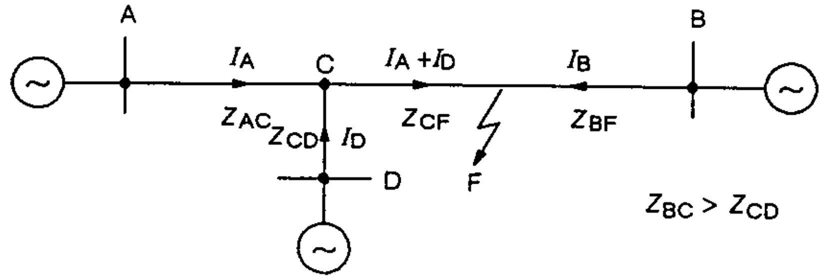



Fig. 5.11: Multi-terminal line

In the case of a three-phase shortcircuit at F a distance relay at A will measure an impedance $Z_{mA}$ dependent of the current ratio $I_D/I_A$:

$$U_A = Z_{AC} \cdot I_A + Z_{CF}(I_A + I_D)$$
$$Z_{mA} = U_A/I_A = Z_{AC} + Z_{CF} + I_D/I_A \cdot Z_{CF}$$

The true impedance between terminal A and the fault is $Z_{AC} + Z_{CF}$. But, due to the intermediate infeed from terminal D, the distance relay at terminal A "sees" an apparent impedance $Z_{mA}$ which is larger. The fault seems to be farther away than it really is.

Different infeed conditions at the terminals and different feeder lengths make the protection problem even more complex to solve with distance protection. See also section 5.7 and ref. [5.5] for the more detailed theoretical background.

If there are no telecommunication facilities available, special distance zone- and time-setting is required to maintain selectivity. For the example of fig. 5.11, the setting of zone 1 of the distance relay at A may then be chosen $0.8 \cdot (Z_{AC} + Z_{CD})$ and the setting of zone 2 at least $1.2 \cdot (Z_{AC} + 2Z_{BC})$ to guarantee also clearing of faults close to the remote terminal. Analogous settings should be chosen for terminal B and D. This setting is called the "FACTOR TWO FORMULA" method. Section 5.7.1.1 provides a detailed guide for the zone setting and the necessary calculation procedures.

The tripping time of zone 2 should be chosen longer than in the rest of the network (e.g. 0.6–0.7sec.), to guarantee a secure selectivity of the time grading.

In general, the protection problems with multi-terminal lines are related to reach problems, intermediate infeed and different feeder lengths.

Another protection problem with respect to multi-terminal lines is the so called "outfeed" condition:

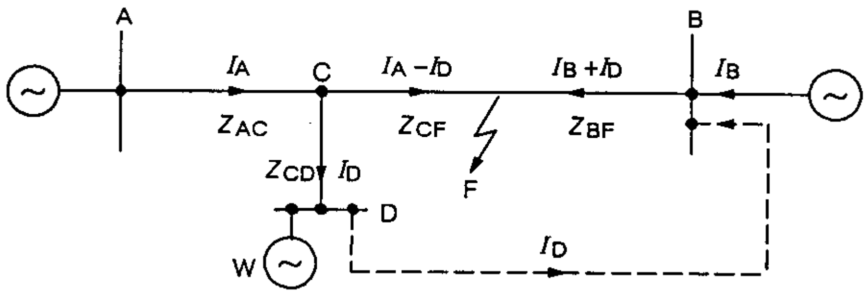



Fig. 5.12: Outfeed condition

This situation may occur in the case of a weak terminal D, interconnected externally to terminal B, so that short-circuit current can flow out of terminal D and contribute to the short-circuit current of terminal B. Under these circumstances directional or phase comparison relays at terminal D may fail to operate because the fault is seen in the reverse direction. See also section 5.7 and ref. [5.5] for the more theoretical background.

## 5.2.2 Tapped lines

The main protection problems with distance relays are in this case related to:

- discrimination between line faults and transformer faults,
- control of the tap-autoreclosure,
- zero sequence infeed from an earthed tap-transformer.

For the solution of these protection problems a current transformer and circuit breaker at the HV-side of the transformer is a decisive advantage. Statistics show that they exist in practice in almost all cases of tapped lines. But there are some exceptions for which solutions have to be found. Generally, it is assumed that current transformers (CTs) are installed at both sides of the tap-transformers that make it possible to use a dedicated transformer differential protection.

### 5.2.2.1 Taps with circuit-breaker (TL 1, TL 2)

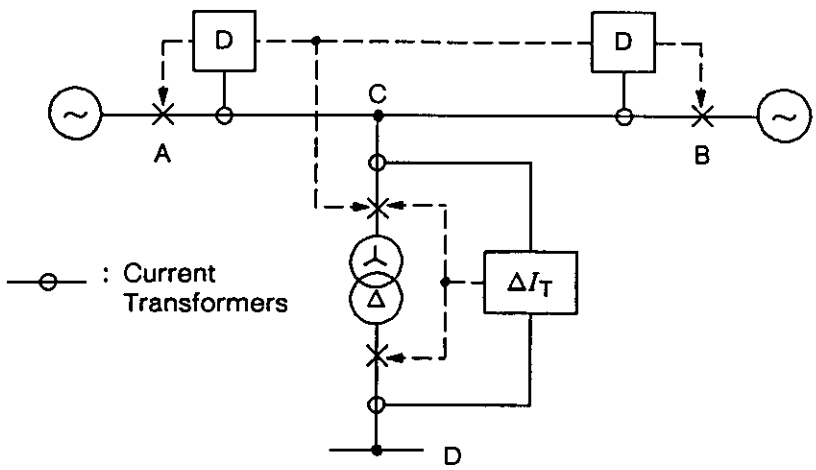



Fig. 5.13: Protection of a tapped line, with circuit breaker at the tap

Possible protection problems:

- When transformer faults occur, there is a risk that both line and transformer will be switched off.
- If single-phase autoreclosure is applied at terminal A and B, then a current contribution from terminal C to the earth-fault in the line will be maintained by the healthy phases through the tap-transformer during the autoreclosure dead time. Therefore, the breaker at C must also be tripped to make deionization of the arc possible.This problem does not occur if 3-phase autoreclosure is applied because the infeed from terminal A and B to terminal C across the healthy phases is then interrupted.
  Independent of the applied reclosure scheme it is always better to decisively trip the breaker at C to prevent reclosing on transformer faults.This tripping of taps may be performed by intertripping or by local criteria, e.g. undervoltage relays, or a combination of both (permissive intertripping).
- Due to earth current infeed from the tap (in the case of an earthed HV-neutral) the problem of high apparent impedances, measured by distance relays at terminals A and B, may cause problems for phase-to-earth faults on line A - B (see section 5.7).
- A solidly earthed tap-transformer presents a zero-sequence current source, i.e. an earth-current flows from the tap to the fault point that is not seen (measured) at the opposite line terminal. This can cause fault detection problems for earth-fault relays.

## 5.2.2.2 Taps without circuit-breaker (TL 3, TL 4)

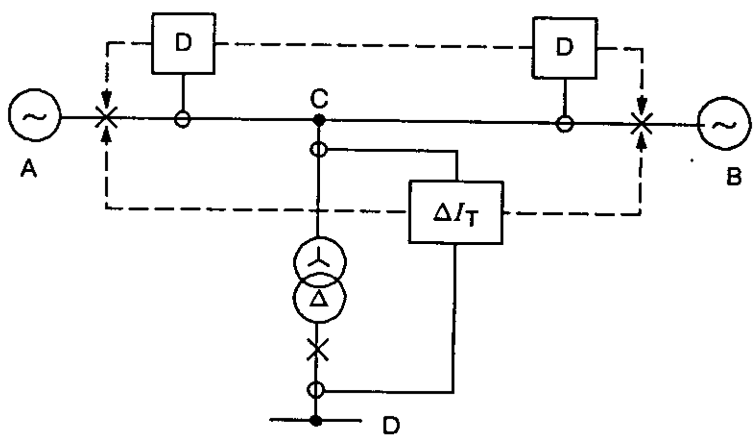



**Fig. 5.14: Protection of a tapped line without circuit breaker at the tap**

Although seldom applied on transmission line level, this configuration should also be treated. The main disadvantage is that line and transformer cannot be separately tripped and consequently,

- single-phase autoreclosure will not be possible: the arc of the line-to-earth fault is sustained from terminal C by infeed via the healthy phases through the transformer windings,
- and in case of three-phase AR it is always possible that reclosure on a transformer fault occurs. This risk has to be weighed against the cost saving of a circuit breaker. Solutions are:
  - blocking of autoreclosure via blocking links to the line terminals,
  - or applying delayed autoreclosure after automatic opening of the tap-isolator (motor-operated disconnector).

### 5.2.2.3 Taps with (small) backfeed (TLB)

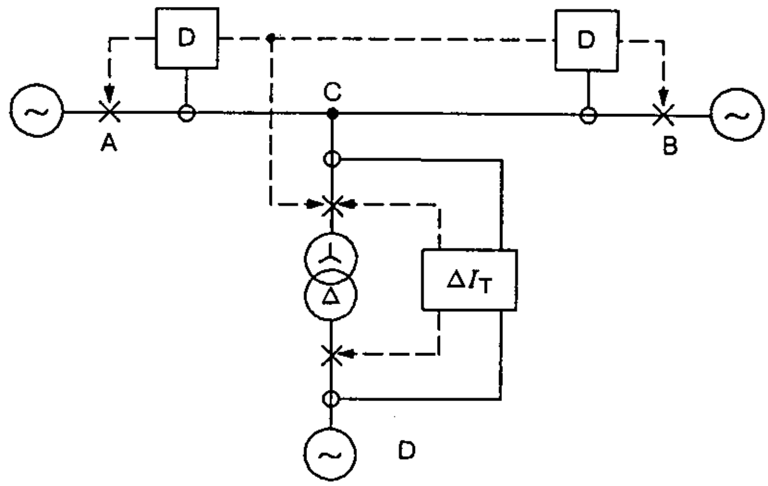



**Fig. 5.15: Tapped line protection, tap with small backfeed**

Normally there is a breaker at the tap point.

The following difficulties may be encountered here:

- Infeed problems
- Fault detection and selectivity problems with weak backfeed can make it difficult to trip the tap in case of line faults (intertripping, tripping by local criteria, or a combination of both).
- Further problems as mentioned under paragraph 5.2.2.1 (taps with breaker).

## 5.3 Protection schemes

The selection of the suitable protection scheme depends mainly on the critical fault clearing time:

- **Delayed fault clearing (e.g. < 1s) and sequential tripping is acceptable.**
  In this case distance and directional or non-directional over-current protection may be suitable, provided that selectivity can be achieved by proper zone- and time-setting.
- **Instantaneous fault clearing (e.g. < 100...150ms) is required.**
  This requirement can generally only be fulfilled by applying communication channels.
  These channels are used to set up command protection schemes with distance or directional earth fault relays. Alternatively unit protection schemes like phase-comparison or differential protection can be planned provided that sufficient bandwidth is available.

## 5.3.1 Protection based on non-unit principles

This kind of protection comprises distance- and directional O/C-relays and the various forms of permissive, non-permissive or blocking type command protection schemes. Local undervoltage- or power directional criteria are sometimes additionally necessary to increase selectivity or to ensure complete isolation of the faulty network section.

### 5.3.1.1 Distance protection without telecommunication

**Multi-terminal lines**

The instantaneous zones are set to underreach the distance from any terminal to the closest remote terminal (as mentioned in 5.2.1). If a fault occurs near the farthest terminal, it may not be seen from the other terminals, certainly not if the source impedances at these terminals are high and the distances to the tap point are very short.

This may result in sequential tripping with delayed fault clearing and consequential consumer supply interruption.

If this can be accepted, selective protection without telecommunication is applicable. Its application in the neighbourhood of power stations may, however, not be admissible because of the danger of instability due to prolonged fault clearing times.

The outfeed problem is difficult to handle only with distance protection (without communication links). In practice the terminals with reverse current will then only be tripped after at least one of the other terminals has opened (sequential tripping).

**Tapped lines**

The problem of distinguishing between line and transformer faults is difficult without telecommunication. However, this deficiency can in many cases be accepted as the probability of transformer faults compared to line faults is low.

The tripping of the tap circuit breakers can be realized by local under-voltage relays (delayed to allow the main line protection to operate first).

In the case of taps without breakers, transformer faults should be covered by zone 2 or 3 of the relays at the main terminals. Fault clearing times may then be long, and there is a risk that the relays will not operate at all due to the high transformer impedance.

Taps with backfeed can be separated from the line during line faults by means of local under-voltage and/or directional relays.

With substantial zero-sequence infeed at the tap (earthed transformer) a distance relay can be used as protection against earth faults.

Proper coordination of the pick-up/drop-out values and provision of an adequate time delay is, however, necessary to prevent overfunction on external faults and to allow a sufficient voltage drop when the taps feed motor load. These application cases prevail on lower voltage levels, mainly on distribution lines. A detailed problem description and relaying solution can be found in references [5.1, 5.2, 5.3].

## 5.3.1.2 Distance protection with telecommunication

**Multi- terminal lines**

The performance of distance relays can be considerably improved if telecommunication channels are available. Then, the local criteria and the received signals from the other terminals can be combined to enable high speed tripping for all terminals (permissive underreach/overreach, blockinĝ overreach and accelerated underreach protection). Zones 2 or 3 provide back-up protection in the case of a telecommunication failure and for faults on the adjacent network sections.

Especially in the case of high source impedances at the terminals, coordination of the fault detection sensivity and the maximum load transmission capacity is necessary. If this is critical, shaped impedance characteristics may be required.

The relays are normally set to underreach the distance to the closest remote terminal:
for example the setting of zone 1 of the relay at terminal A in fig. 5.11 may be $0.8 \cdot (Z_{AC} + Z_{CD})$.

The setting of zone 2 may be 1.2 times the maximum apparent impedance to the farthest terminal or the setting mentioned in 5.2.1: $Z_2 = 1.2\ (Z_{AC} + 2 \cdot Z_{BC})$ with a time delay of 0.6 to 0.7s.

Time-coordination with the zone 2 times in the rest of the network is important to ensure selectivity.

If one terminal is open (circuit-breaker switched off) for some time, for example during maintenance, the relays of the other terminals may be set to underreach the distance to the remaining remote terminal each. For example in fig. 5.11: if terminal D is open, the reach of zone 1 of the relays at A and B could be $0.8 \cdot (Z_{AC} + Z_{BC})$.

In blocking overreaching schemes the reach of the reverse looking blocking zone must be set large enough to detect all reverse external faults that can be seen by the overreaching tripping zones of the remote line ends. As compared to two-terminal lines a higher setting may be necessary due to the infeed-effect through the third terminal (calculation procedure similar to 5.7.1.2).

Outfeed situations are better dealt with by an underreaching scheme with a non-directional permissive criterium like underimpedance, overcurrent or undervoltage. See fig. 5.12: if $I_D$ is high enough to start the relay at D, the start criterium and the trip enable signals from the terminals A and B can be combined to get tripping at terminal D. Otherwise undervoltage criteria or direct intertripping would have to be applied.

All schemes using directional overreaching or blocking zones as well as zone acceleration schemes are not suitable at terminals with possible outfeed conditions.

**Tapped lines**

With telecommunication it is possible to be more selective in distinguishing between line and transformer faults, provided there is a breaker at the tap. In case of a transformer fault a blocking signal from the transformer protection to the relays at terminals A and B (fig. 5.13) prevents these relays from tripping the line. This requires however that the zone 1 time of the main line relays must be delayed for some milliseconds to allow the secure arrival of the blocking signal.

If there is a breaker at terminal C, then it can be intertripped for faults on the main line. It is also possible to reclose the breaker again. But in general, if no special measures are taken to distinguish between line and transformer faults, it is better to decisively trip the tap breaker. Permissive local criteria for tripping the tap breaker, like under-voltage, may be used in combination with intertrip signals to improve the security (especially in cases of weak infeed).

The settings of the distance zones at terminals A and B correspond to the normal two-terminal lines in the rest of the network.

Distance reach problems may arise for single-phase-to-earth faults due to the earth current source of the tap transformer. A permissive or accelerated scheme is recommended to cope with these problems. For the setting of the overreaching zones the "FACTOR TWO FORMULA" method is recommended (see 5.2.1).

Shaped distance zone characteristics may be necessary to limit the reach in resistive direction and to avoid liability to load encroachment and power swing.

In the case of taps without breakers (fig. 5.14) transformer faults should be cleared by sending intertripping and autoreclosure blocking signals from the transformer protection to the breakers at terminals A and B. In general, autoreclosure may be a risk with this line configuration because of the chance to reclose onto a transformer fault, unless special measures are taken to block reclosure by means of signals from the transformer protection or from a directional blocking device at the tap. This risk of damaging a transformer must be weighted against the cost saving of protection and telecommunication equipment. This depends largely on the individual utility's practical experience.

If high resistance earth-faults are likely to occur, application of separate earth-fault relays is recommended (directional over-current relays). They can be used alternatively or in parallel with overreaching distance relay zones in directional comparison schemes.

For tapped lines with backfeed (fig. 5.15) it is advisable to intertrip the transformer breaker from the protection at both line ends during line faults, to prevent infeed from the tap. Under-voltage and/or directional power relays at the taps themselves can also be applied as back-up against communication failures. Time-setting and voltage setting of under-voltage relays have to be carefully chosen to be selective with external faults [5.1, 5.2].

High-speed tripping of the taps during line faults is also important for succesful fast autoreclosure: it must be ensured that the fault arc extinguishes and the arc path is deionized [5.2].

The infeed problems of taps with backfeed (fig. 5.15) may be solved in a similar way like with multi-terminal lines, by applying permissive, blocking or accelerated schemes for terminals A and B with intertrip signals to terminal C. Application of permissive intertripping is advised to improve security.

Tapped line protection applied on the EHV-level can require quite a high number of communication links, especially when single phase autoreclosure is applied [5.25]:

- Intertripping links per phase from each line terminal to the tap if single phase AR is practised.
- Signal link to block the main line protection in case of a transformer fault.
- Breaker-failure intertrip links.
- Possibly reclosing links.

### 5.3.1.3 Directional comparison protection

With this type of protection the direction of current or the direction of the short-circuit power of all terminals is compared. If all measured directions point into the protected area, an internal fault is detected. If one or more currents or powers flow out of the protected area, it is an external fault.

The protection scheme is very similar to the permissive overreach distance protection scheme.

The relays are generally started or released by over-current or underimpedance criteria. The direction signs are transmitted to the other terminals. If at any terminal equality of all signs is established, tripping of this terminal will follow.

**Multi-terminal lines**

For multi-terminal lines, directional comparison protection is successfully applicable unless outfeed conditions can occur. If currents or powers flow out of the protected area at one or more terminals in case of an internal fault, this protection scheme would consequently fail.

The starting relays should be set to overreach the remotest terminal under the worst circumstances with respect to short-circuit power and infeed; they should not start at the highest possible load current. For directional earth-fault relays sensitive settings are possible as the load current does not need to be taken into account. Normally, such schemes have low set current starters for the release of the directional measurement and the initiation of the signal transmission. A high set current element is provided to enable tripping. The low set element should have picked-up before tripping is released at any line end. It has to be considered that a larger setting difference margin is necessary for 3-ended lines compared to two-ended lines.

**Tapped lines**

For tapped lines, a directional comparison scheme is also entirely suitable. In the case of fig. 5.13, with earthed HV-neutral, infeed from the tap can only take place when earth-faults occur on the HV-level. It may therefore be sufficient to provide the tap transformer with over-current earth-fault relays at the HV-side.

The relays at A should be set to overreach terminal B and the relays at B should be set to overreach terminal A.

The relay at C should be set to overreach the farthest of the terminals A and B.

The transformer is protected locally by its own protection that trips the allocated circuit breaker.

Taps without a breaker (fig. 5.14) can be selectively protected by applying directional relays at terminals A and B, overreaching the transformer. A blocking element at the low voltage side would have to be added.

If the HV-neutral is earthed, an autoreclosure scheme may be admitted by adding a blocking device at the tap.

This device consists of a directional over-current or a power relay that blocks autoreclosure if the fault is located in the transformer. If a separate transformer differential relay or gas pressure protection is available, blocking can also be realized by deriving a blocking signal when these protections operate.

At taps without a breaker, tripping should always be three-phase because these taps would feed current into earth-faults and would prevent arc extinction as just mentioned above.

Taps with small backfeed (fig.5.15) may also be equipped with a directional comparison scheme, in which terminals A, B and C are included. This scheme covers also two- and three-phase faults, because there exists adequate infeed from the tap.

In case of low infeed from the tap an under-voltage criterion, as with passive taps, must be added.

### 5.3.2 Power line protection based on unit principles

Protection principles that compare analogue measuring values from all terminals of the line configuration enable absolutely selective protection schemes less sensitive to infeed conditions. In the normal case,the measuring quantities are transmitted from each terminal to all other terminals.

Pilot wire differential protection has been limited to distances in the order of 20km. By applying wide band telecommunication, like microwave or optical fibre links, it is now also possible to protect long HV-lines up to the order of 100km with unit type protection [4.22].

#### 5.3.2.1 Phase comparison protection

This protection principle is based on the measurement of the phase angle difference between the line currents of the different terminals. If the phase angle difference exceeds a certain stabilizing angle, tripping of the line will occur.

Two kinds of protection are available: segregated and non-segregated phase comparison. If single pole autoreclosure is being applied, then a segregated system, protecting each phase separately, is recommended as it provides absolute phase- and zone selectivity independent of additional phase-selectors.

The phase comparison protection has moderate requirements on the bandwith of the transmission-channel as only current phase-positions (square waves) have to be transmitted. A one kHz slot of a voice channel is sufficient for a non-segregated protection. Segregated protection needs about 4kHz.

**Multi-terminal lines**

Phase comparison protection is by principle suitable for multi-terminal lines. It needs, however, infeed from all terminals (In the case of a weak-infeed terminal, the "infeed" condition must be simulated by generating a release signal if the PCP-starting elements do not operate).

Basically this protection is designed for comparing two quantities. So there is normally a problem of mixing the phase-information of three or more quantities. Moreover, one must be sure that no outfeed condition can occur at any terminal that would block the relay. The reason is that the phase-angle of the current would change in this case by 180° when outfeed occurs, no matter how small the current is, thus simulating an external fault. For these reasons phase comparison protection is seldom used on multi-terminal lines.

**Tapped lines**

In the case of fig. 5.13 (tap with breaker), the terminals A, B and C can be equipped with phase comparison relays. Together with the transformer protection a selective unit protection scheme for the tapped line configuration can then be achieved.

A segregated protection system should again be preferred if single pole autoreclosure is practised.

Tapped lines without a breaker (fig. 5.14) may be equipped with phase comparison relays only at terminals A and B.

It has, however, to be guaranteed that under load and through-fault conditions the load current at the tap will not cause a phase shift between $I_A$ and $I_B$ that exceeds the set blocking angle of the PCP. For faults in the tap-transformer or at the low voltage side, the PCP may however operate.

Blocking signals from a blocking device at the tap or from the transformer protection can prevent unwanted tripping and reclosing in this case.

Autoreclosure must be three-phase, because otherwise the voltage on the faulted phase would be maintained during earth faults.

Phase comparison protection would also be applicable for taps with small backfeed (fig. 5.15). The relays should be located at terminals A, B and C. The protection system should preferably be of the phase segregated type if single pole autoreclosure is applied.

For the same reason as for multi-terminal lines (outfeed condition) the PCP is practically not often used on lines with high load taps.

### 5.3.2.2 Longitudinal differential protection

This protection principle is based on the vectorial summation of the currents of all terminals. To achieve this, momentary or phasor quantities of the currents are measured and transmitted. For load or through-fault conditions the sum of the currents is nearly zero. The relay operates when the sum exceeds the set threshold level. Segregated and non-segregated systems are also available. Single pole autoreclosure is possible if each phase is separately protected by its own differential protection system. In case of a composite type relay additional phase selectors would be necessary.

The phase segregated type should be preferred for single pole AR as it provides equally phase- and zone-selectivity.

**Multi-terminal lines**

From the protection point of view (selectivity, speed), probably the best protection system for multi-terminal lines is longitudinal differential protection. It even widely covers outfeed conditions, as not only the phase-angle information, but also the current magnitude is used. See section 5.7 for more background information.

**Tapped lines**

Longitudinal differential protection may also be applied on tapped lines, if the tap current is included in the summation.

This means for the configuration in fig. 5.13 (tap with breaker) that relays should be installed at the terminals A, B and C. In this way line and transformer can be protected separately.

For applying single pole autoreclosure a segregated system should be preferred. This type has the advantage of strict selectivity and voltage transformers for phase selection are not required at the tap(s).

Tapped lines without breaker (fig. 5.14) should also be protected at terminals A, B and C, if a separate transformer protection is installed with intertripping links to the breakers at A and B. Single pole autoreclosure is not possible in this case as the fault would be fed by the healthy phases through the tap transformer.

Another way to protect this configuration is by installing differential relays at terminals A, B and D. Autoreclosure should be blocked then if there is a fault in the transformer. This may be realized by a blocking device at terminal C ( reverse current or power). The protection scheme would then, however, have to be stabilized against the inrush current of the tap transformer.

Longitudinal differential protection is also suitable for taps with small backfeeds (fig. 5.15). The relays should be located at terminals A, B and C. The protection system should again preferably be of the segregated type if single pole autoreclosure is to be applied.

### 5.3.3 Back-up protection

Multi-terminal and tapped lines require careful consideration of the back-up protection especially as concerns fault detection sensivity and provision of intertripping links.

Remote back-up may create problems due to the more critical infeed problem. As a consequence of the three-terminal configuration two intermediate infeeds exist for external faults. In addition to the remote-terminal infeed an "in-line" infeed has to be taken into account (see fig. 5.16).

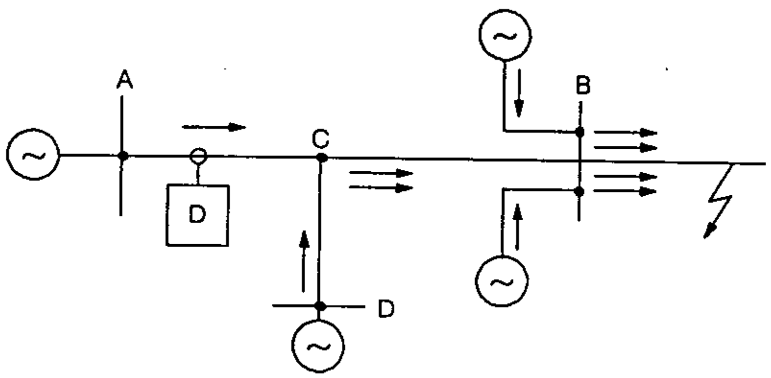



Fig. 5.16: Three terminal line with remote back-up

Therefore, the zone reach is two-fold reduced and may not be sufficient to provide reasonable line coverage. In the worst case the back-up zone may not even reach the remote terminals. In this case local back-up protection is indispensable. Intertripping links have additionally to be provided to both remote terminals.

## 5.4 Automatic reclosing considerations

In general it can be stated that automatic reclosing can be applied both on multiterminal and tapped lines without problems. There is only one limitation: If the breaker at the tap cannot be tripped by the protection or if there is no breaker at the tap, then single pole autoreclosure cannot be applied because of the coupling of voltage from the healthy phases to the faulted phase through the tap transformer.

Lines in the neighbourhood of power stations may be excluded from three phase reclosing at the generator side of these lines to prevent very high generator shaft torques at reclosing on close-in two- and three-phase faults.

This is, however, generally valid and must not be considered as a special case of multiterminal or tapped lines. It is only mentioned here because power plants are often branched-in through line taps.

## 5.5 Recent practices and trends

### 5.5.1 General remarks

The replies to a CIGRE questionnaire circulated in 1989 (see also section 4.6) brought forward in this case the following (see tables 5.1 to 5.3):

- The use of multiterminal and tapped lines is common in most countries, at all voltage levels.
- In general there is no tendency to apply multi-terminal and tapped lines more often with exception of 110/150kV-networks, where tapped lines seem to be wide-spread.
- Wide band communication like microwave and optical fibre, is the future trend also for protection purposes.

| | > 300 kV | 200 - 250 kV | 100 - 150 kV |
|---|---|---|---|
| Total number of lines (49 utilities) | 1684 | 3438 | 9277 |
| MTL | 40<br>2.37% | 185<br>5.38% | 233<br>2.51% |
| TL | 41<br>2.43% | 96<br>2.79% | 1025<br>11.05% |
| Number of taps | 1 or 2 | 1 to 4 | 1 to 8 |
| tendency to apply more often MTL ? | Yes : 8<br>No : 23 | Yes : 10<br>No : 21 | Yes : 8<br>No : 19 |
| TL ? | Yes : 3<br>No : 23 | Yes : 7<br>No : 21 | Yes : 16<br>No : 11 |

**Table 5.1: Existing multi-terminal lines (MTL) and tapped lines (TL)**

| | % of utilities use on multiterminal lines (MTL) and tapped lines (TL) | | | | | |
|---|---|---|---|---|---|---|
| | > 300 kV | | 200 - 250 kV | | 100 - 150 kV | |
| | MTL | TL | MTL | TL | MTL | TL |
| Distance protection without telecommunication | 8% | 25% | 14% | 26% | 40% | 54% |
| Distance protection with telecommunication | 62% | 50% | 71% | 65% | 40% | 38% |
| Phase comparison protection | 7% | 5% | - | 4% | - | - |
| Differential protection | 23% | - | 14% | 5% | 20% | 8% |
| Sensitive earth fault relays | 25% | 25% | 38% | 48% | 40% | 38% |

**Table 5.2: Multi-terminal and tapped lines, applied protection schemes**

| |
|---|
| • Selectivity problems with MTL ?<br>Yes : 31%<br>No : 27%<br>No statement : 42%<br>(of utilities) |
| • If "Yes", what kind ? — Number of answer<br>- Different feeder lengths : 8<br>- Distance-zone reach problems : 7<br>- Weak infeed conditions : 10<br>- Outfeed conditions : 3<br>- Failure of telecommunication : 4<br>- Reason not named : 2 |
| • Intention to use more often Wideband channels:<br>Yes : 48% — Microwave :14%; Optical fibre :17%; Both :17%<br>No : 19%<br>No answer : 33% |

**Table 5.3: Multi-terminal lines (MTL), protection aspects**

### 5.5.2 Multi-terminal lines

- The protection schemes used do in general not depend on the network configurations considered (chapter 5.1.2). Most frequently applied is distance protection with telecommunication.
  The same is valid for complex multi-terminal lines.
- The number of companies having selectivity problems with their protection schemes is about equal to the number of companies having not. The major reported problems are reach problems, different feeder lengths and weak infeeds.

### 5.5.3 Tapped lines

- The number of taps per line varies from 1 to 11.
- Almost all companies have taps with circuit-breakers at the HV-side of the tap-transformer.
- The most frequently applied configurations are TL 1 and TL 2 (chapter 5.1.2).
- Practically all companies use distance protection with telecommunication.
- 80% of the companies apply autoreclosing on tapped lines. On higher voltage levels single phase autoreclosing is frequently applied, on lower voltage levels three phase autoreclosing is the rule.
- The lower the voltage level, the higher the number of utilities that do not trip the taps.
- Tripping of taps is most frequently realized by under-voltage relays with or without permissive intertripping from the main terminals.
- 62% of the companies have taps with backfeed. The taps are in most cases tripped by directional over-current- or power relays.
- On higher voltage levels reclosing of taps is often performed by dedicated autoreclosing devices at the tap. On lower voltage levels manual local or remote reclosure prevails.
- 33% of the companies use shaped relay characteristics to cover increased apparent fault impedances and to avoid problems with load encroachment and power swing.

## 5.6 Application examples

Protection of multi-terminal lines, example 1

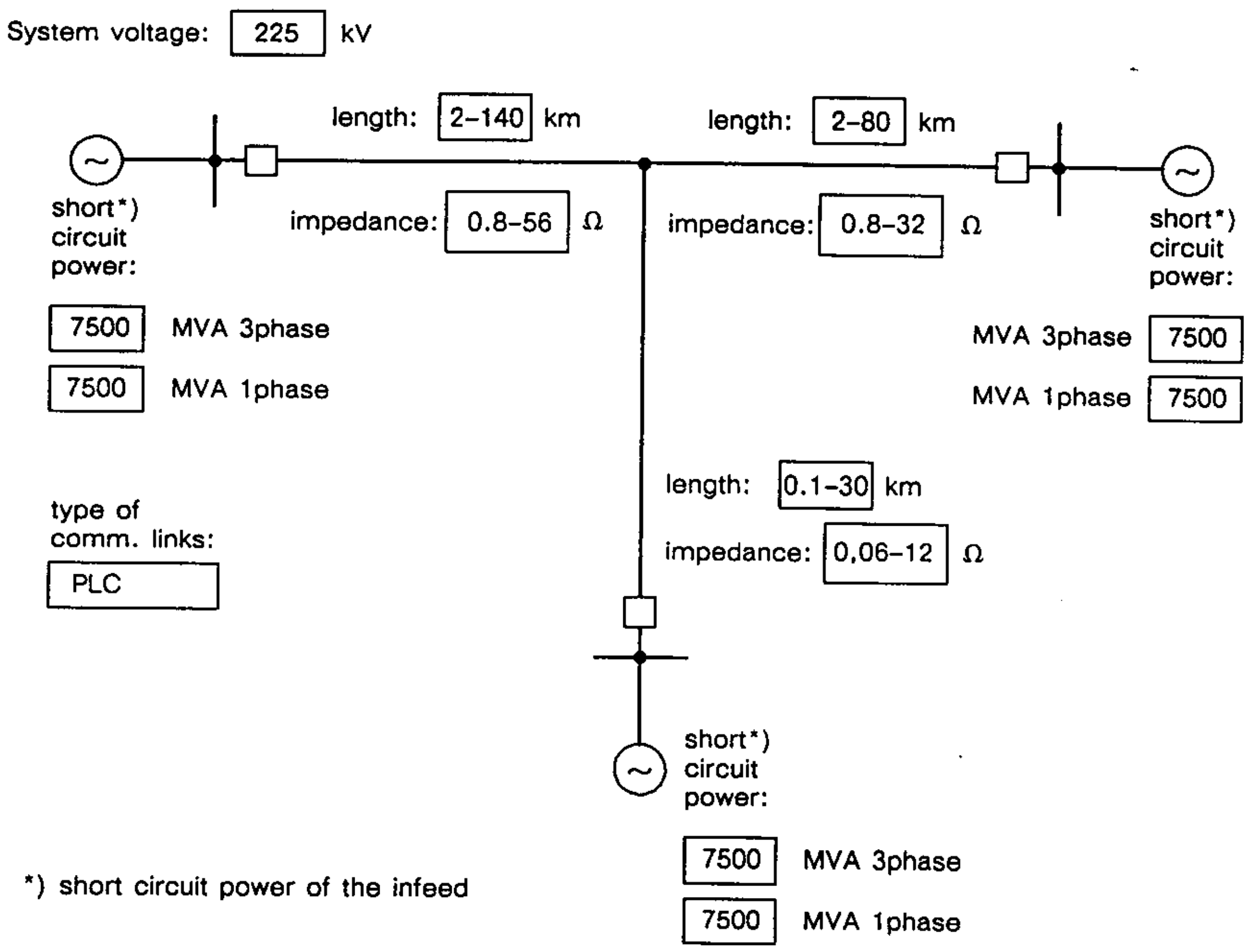



Fig. 5.17

Brief description of the applied protection systems:

**Primary (Main 1-) Protection:**

Today: distance protection

Near future: Current differential protection

**Secondary (Main 2 or back-up) Protection:**

Distance protection

Under voltage supplement as permissiive criterium for weak-infeed conditions

## Protection of multi-terminal lines, example 2

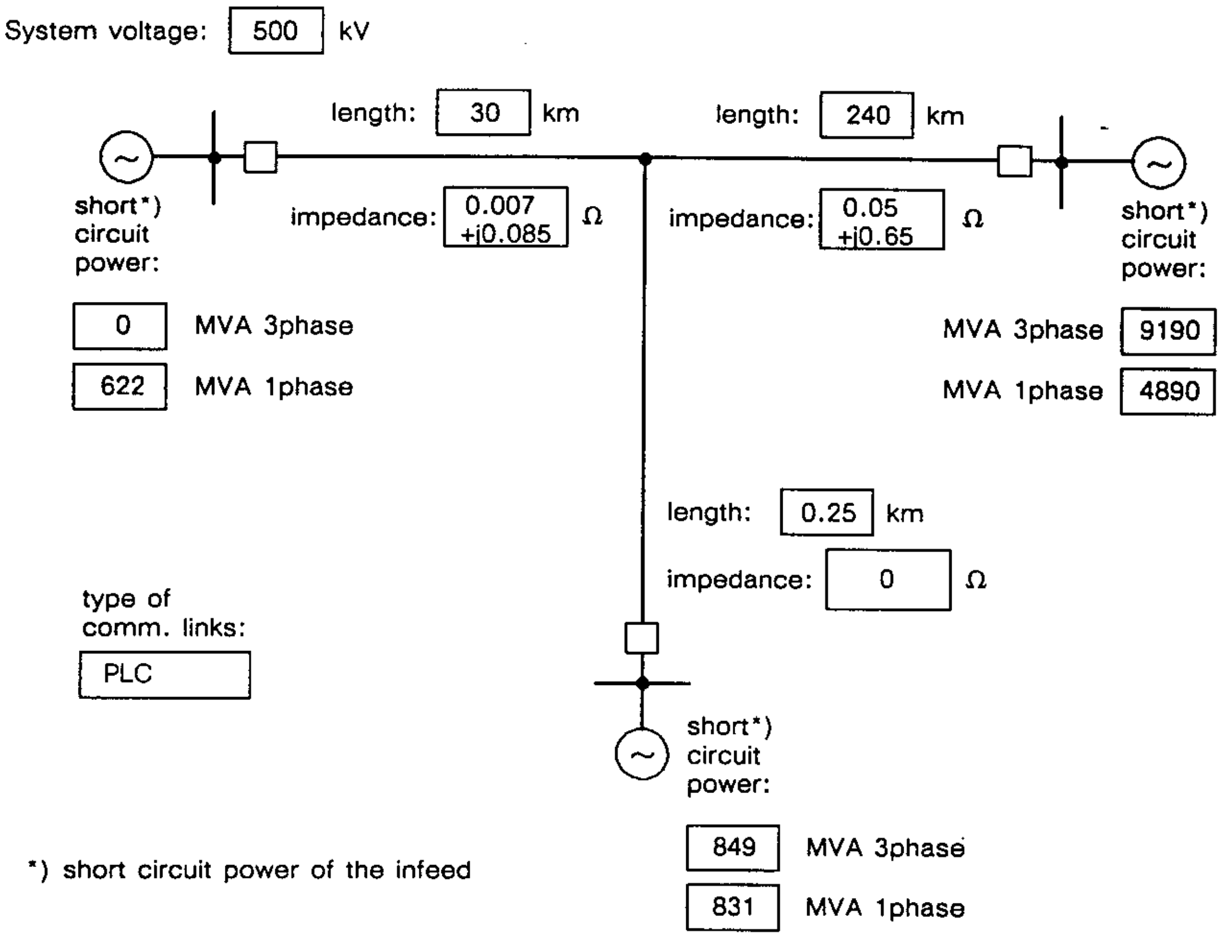



Fig. 5.18

Brief description of the applied protection systems:

**Primary (Main 1-) Protection:**

Distance protection operating in an overreaching blocking mode in conjunction with power line carrier communication links. As there are two parallel lines on the same tower, there is very strong mutual coupling between the lines. As a result, zone 1 is set to 50% $Z_L$, while zone 2 is set to 200% $Z_L$ to protect the lines under all conditions that may exist, including that of switching out and earthing both ends of the parallel line.

**Secondary(Main 2 or back-up) Protection:**

Distance protection operating in an overreaching permissive intertrip mode in conjunction with a power line carrier communication link. Same settings apply as for Main 1 Protection.

## Protection of multi-terminal lines, example 3

single-pole autoreclosing only, with prolonged 1st zone equal to $Z_2$, dead time = 1s

System voltage: 220 kV

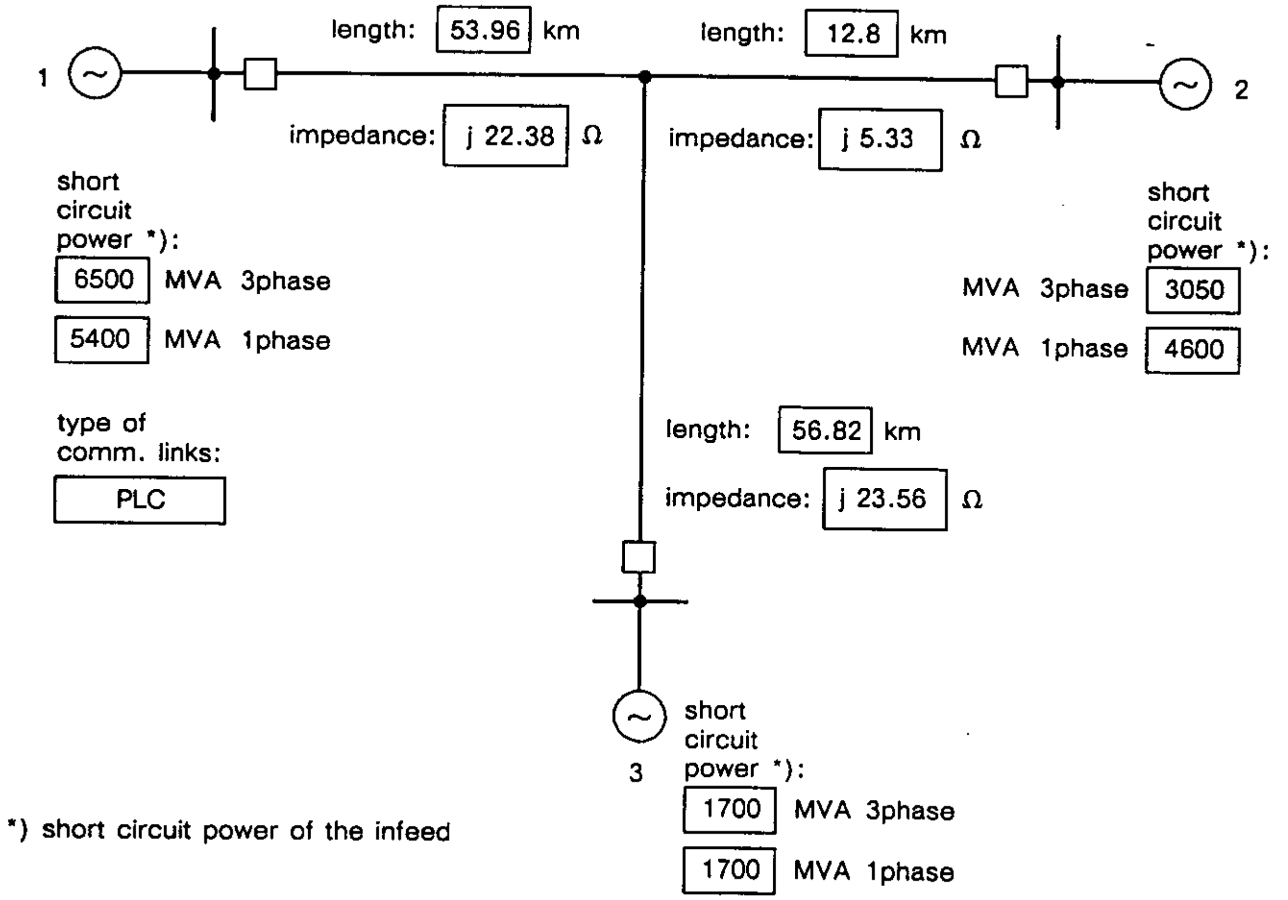



**Fig. 5.19**

Brief description of the applied protection systems:

**Primary Protection: PODP**

Distance protection using telecommunication

**Secondary Protection: DPZS**

| | | | |
|---|---|---|---|
| Terminal 1: | $Z_1$ = 22.17Ohm | $Z_2$ = 1.20(22.38 + 2x23.56)Ohm (0.7s) | $Z_3 = 1.3 \cdot Z_2$ ( 1.1s) |
| Terminal 2: | $Z_1$ = 22.17Ohm | $Z_2$ = 1.20(5.33 + 2x23.56)Ohm (0.7s) | $Z_3 = 1.3 \cdot Z_2$ ( 1.1s) |
| Terminal 3: | $Z_1$ = 23.40Ohm | $Z_2$ = 1.20(23.56 + 2x22.38)Ohm (0.7s) | $Z_3 = 1.3 \cdot Z_2$ ( 1.1s) |

(Setting calculations with the FACTOR TWO FORMULA, see page 91)

Protection of tapped lines, example 1

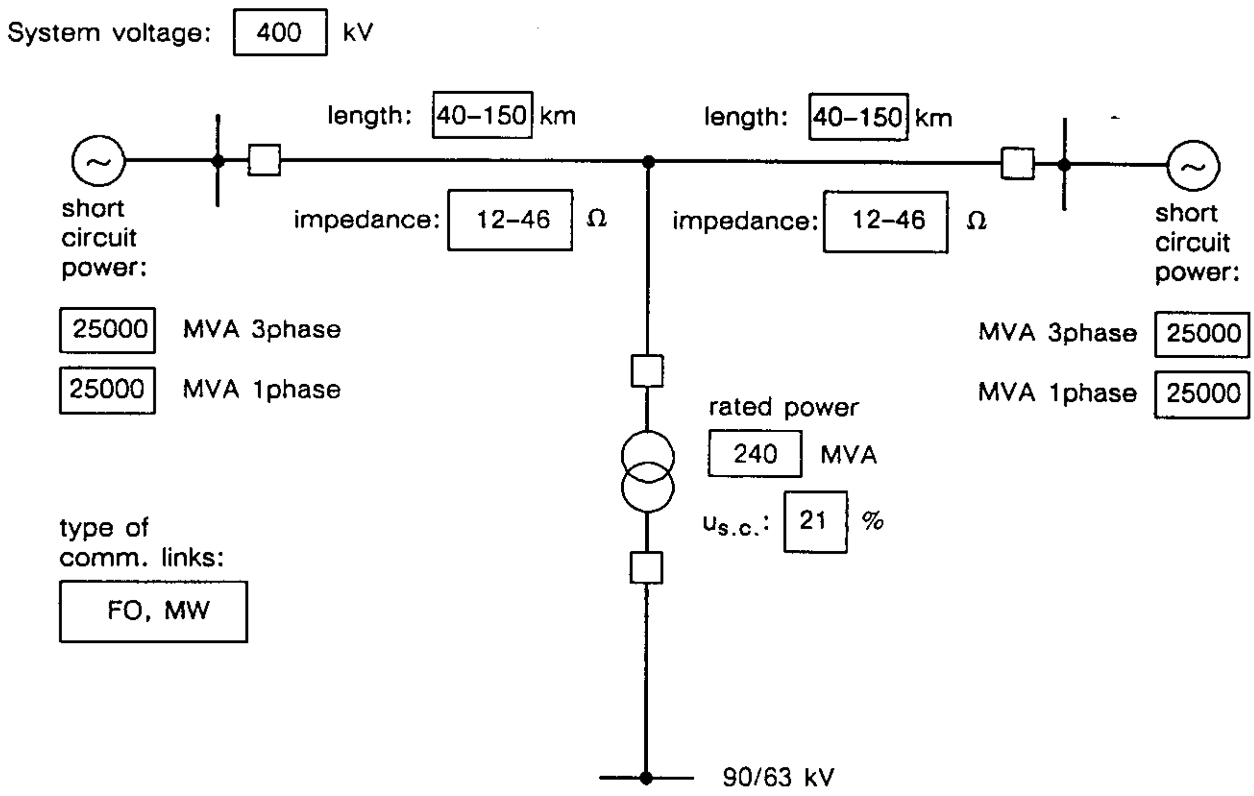



Fig. 5.20

Brief description of the applied protection systems:

**Primary Protection:**

Differential protection

**Secondary Protection:**

Distance protection without telecommunication

**Tap Protection:**

Under-voltage protection (PTT)

Protection of tapped lines, example 2

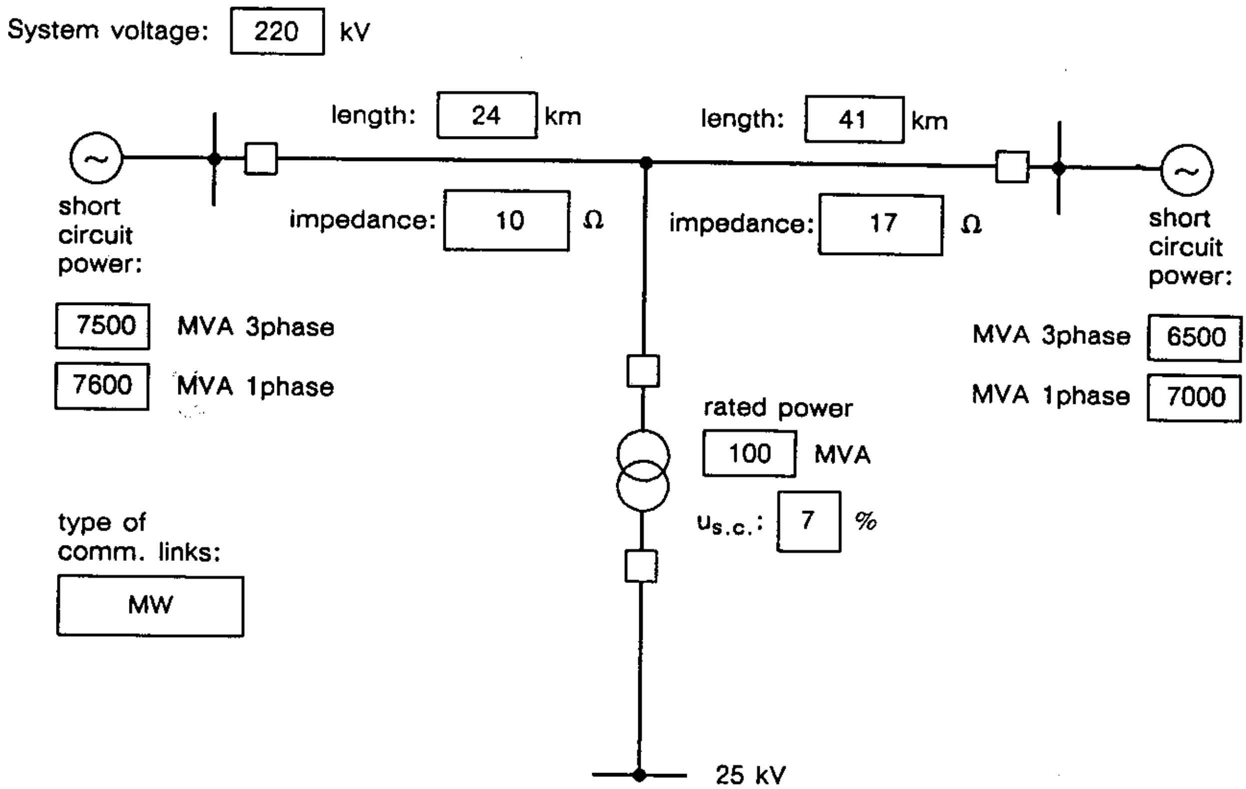



Fig. 5.21

Brief description of the applied protection systems:

**Primary Protection**

Accelerated underreach distance protection with intertripping signal to the tap

**Secondary Protection:**

Directional earth fault protection, time delayed without telecommunication

## 5.7 Appendices

In these appendices some examples are given for the calculation of relay settings and really measured impedances. These calculations are made by hand, to get a feeling for the problems. In practice there are various computer programs available for this purpose.

### 5.7.1 Multi-terminal lines

#### 5.7.1.1 Infeed conditions

In the following, expressions are derived for the fault-impedances seen from the line-terminals in case of a 3-phase fault. Further, formulas for the current distribution are developed.

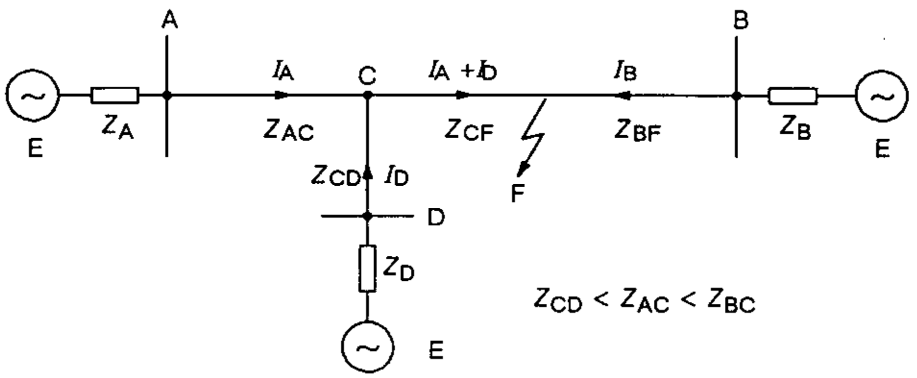



Fig. 5.22

The sources are assumed to have the same voltage E and the same phase-angle. Prefault load is neglected. Herewith the following equations are valid:

$$U_A = I_A Z_{AC} + (I_A + I_D) Z_{CF} = E - Z_A I_A \quad 1)$$
$$U_B = I_B Z_{BF} = E - Z_B I_B \quad 2)$$
$$U_D = I_D Z_{CD} + (I_A + I_D) Z_{CF} = E - Z_D I_D \quad 3)$$

From expr. 1) the following measured impedance for the relay at A can be derived:

$$Z_{mA} = U_A / I_A = Z_{AC} + (1 + I_D / I_A) Z_{CF} \quad 4)$$

Subtracting 3) from 1) delivers:

$$I_A (Z_A + Z_{AC}) = I_D (Z_D + Z_{CD})$$
$$I_D / I_A = (Z_A + Z_{AC}) / (Z_D + Z_{CD}) \quad 5)$$

By introducing 5) into 4) we get:

$$U_A / I_A = Z_{AC} + \left(1 + \frac{Z_A + Z_{AC}}{Z_D + Z_{CD}}\right) Z_{CF} \quad 6)$$

(two-terminal line: $U_A / I_A = Z_{AC} + Z_{CF}$)

In the same way expressions can be found for $U_B / I_B$ and $U_D / I_D$.

These measured apparent impedances must be compared with the setting of the relays to determine if reach problems can occur due to the infeed effect:

**Setting of zone 1:**

| Measured impedances | Settings (first zone) | |
|---|---|---|
| $Z_{mA} = U_A/I_A = Z_{AC} + (1 + \frac{Z_A + Z_{AC}}{Z_D + Z_{CD}})Z_{CF}$ | $0.85(Z_{AC} + Z_{CD})$ | 7) |
| $Z_{mB} = U_B/I_B = Z_{BF}$ | $0.85(Z_{BC} + Z_{CD})$ | 8) |
| $Z_{mD} = U_D/I_D = Z_{CD} + (1 + \frac{Z_D + Z_{CD}}{Z_A + Z_{AC}})Z_{CF}$ | $0.85(Z_{AC} + Z_{CD})$ | 9) |

The above settings are chosen for the case that $Z_{CD} < Z_{AC} < Z_{BC}$.

Substituting 5) in 1) results in a formula for $I_A$:

$$I_A = \frac{E}{Z_A + Z_{AC} + (1 + \frac{Z_A + Z_{AC}}{Z_D + Z_{CD}})Z_{CF}} \qquad 10)$$

In the same way $I_B$ and $I_D$ can be derived:

$$I_B = \frac{E}{Z_B + Z_{BF}} \qquad 11)$$

$$I_D = \frac{E}{Z_D + Z_{CD} + (1 + \frac{Z_D + Z_{CD}}{Z_A + Z_{AC}})Z_{CF}} \qquad 12)$$

It can be seen from the expressions 7, 9, 10 and 12 that the worst case with respect to reach problems will occur if:

- The leg BC is very long compared to the legs AC and CD.
- The source impedances $Z_A$ and $Z_D$ are very high.
- A fault occurs in the neighbourhood of substation B.

If we assume for example that $Z_A + Z_{AC} \approx Z_D + Z_{CD}$ and that $Z_{CF} = 3Z_{AC} = 3Z_{CD}$, then the relays at A and D will see an apparent impedance of $3.5(Z_{AC} + Z_{CD})$. This corresponds to about four times the setting of the 1st zone. The currents at terminal A and D are $E/(Z_D + 7Z_{CD})$. These minimum fault currents must be compared with the highest possible load currents when the setting of O/C fault detectors is considered.

**Setting of the overreaching zones** (FACTOR TWO FORMULA)

The overreaching zones should at least see a fault near the farthest line-end of the multi-terminal line.

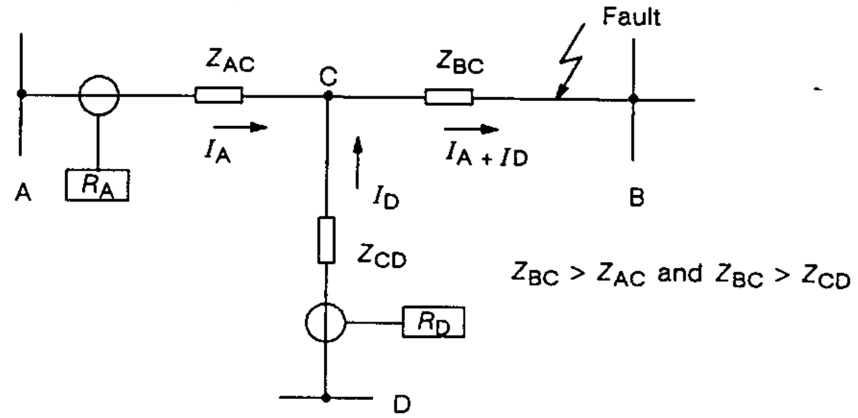



**Fig. 5.23**

For example, a fault at B should at least be seen by Relay $R_A$ or $R_D$.If one relay trips, the other relay will also see the fault and trip because the intermediate infeed at point C is removed.

The relays $R_A$ and $R_D$ measure the following impedances:

$$Z_{mA} = Z_{AC} + \frac{I_A + I_D}{I_A} \cdot Z_{BC} = Z_{AC} + Z_{BC} + \underbrace{\frac{I_D}{I_A} \cdot Z_{BC}}_{\text{Error A}}$$

$$Z_{mD} = Z_{CD} + \frac{I_A + I_D}{I_D} \cdot Z_{BC} = Z_{CD} + Z_{BC} + \underbrace{\frac{I_A}{I_D} \cdot Z_{BC}}_{\text{Error D}}$$

The errors A and D can not be larger than $Z_{BC}$ at the same time, because either $I_D/I_A$ or $I_A/I_D$ is smaller than 1. The worst case is given when $I_A$ and $I_D$ are equal. In this case the error is $Z_{BC}$ for both relays. In order to enable at least one relay to see the fault near B, the following minimal setting can be deduced (20% safety margin):

$Z_{RA} = (Z_{AC} + 2 \cdot Z_{BC}) \cdot 1.2$

$Z_{RD} = (Z_{CD} + 2 \cdot Z_{BC}) \cdot 1.2$

In general we get the following formula for the setting of the overreaching zones:

$Z_{OR} = (Z_X + 2 \cdot Z_Y) \cdot 1.2$

where $Z_X$ = impedance from the relay to the junction point (C)
$Z_Y$ = impedance from the junction point (C) to the impedance-wise farthest other terminal.

This setting approach is called the "FACTOR TWO FORMULA" method.

**Setting for single-phase-to-earth faults:**

In the same way calculations may be carried out for single-phase-to-earth faults. In this case the zero sequence impedances and the zero sequence infeeds have a strong influence. Additional reach problems may arise due to mutual coupling with parallel circuits.

For single-phase-to-earth faults the apparent impedance is not only determined by the relative length of the legs, but also by the zero-sequence infeeds and the $Z_0/Z_1$ ratio of sources and legs.

Moreover, the $k_0$-factors are very sensitive to the state of the parallel circuits (in service or out of service and earthed). This effect is treated in section 4.2.1.1.2).

Example: (see fig.5.24)

Suppose that there is a single-phase-to-earth fault in location F. The impedances measured by the relays at A, D and B can then be derived from the series-connected sequence-networks as demonstrated in the following figure 5.24.

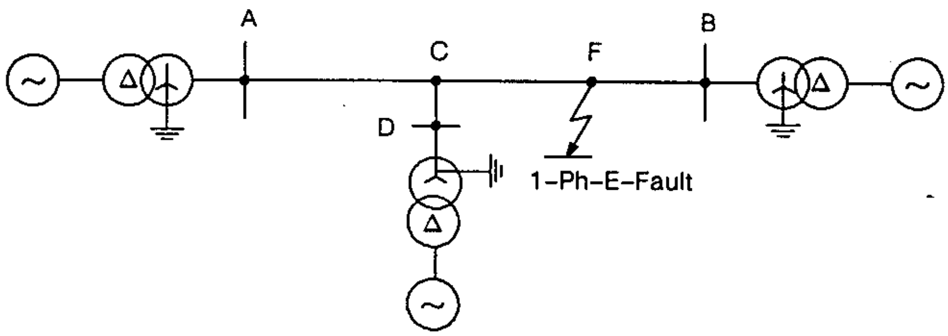



Fig. 5.24a

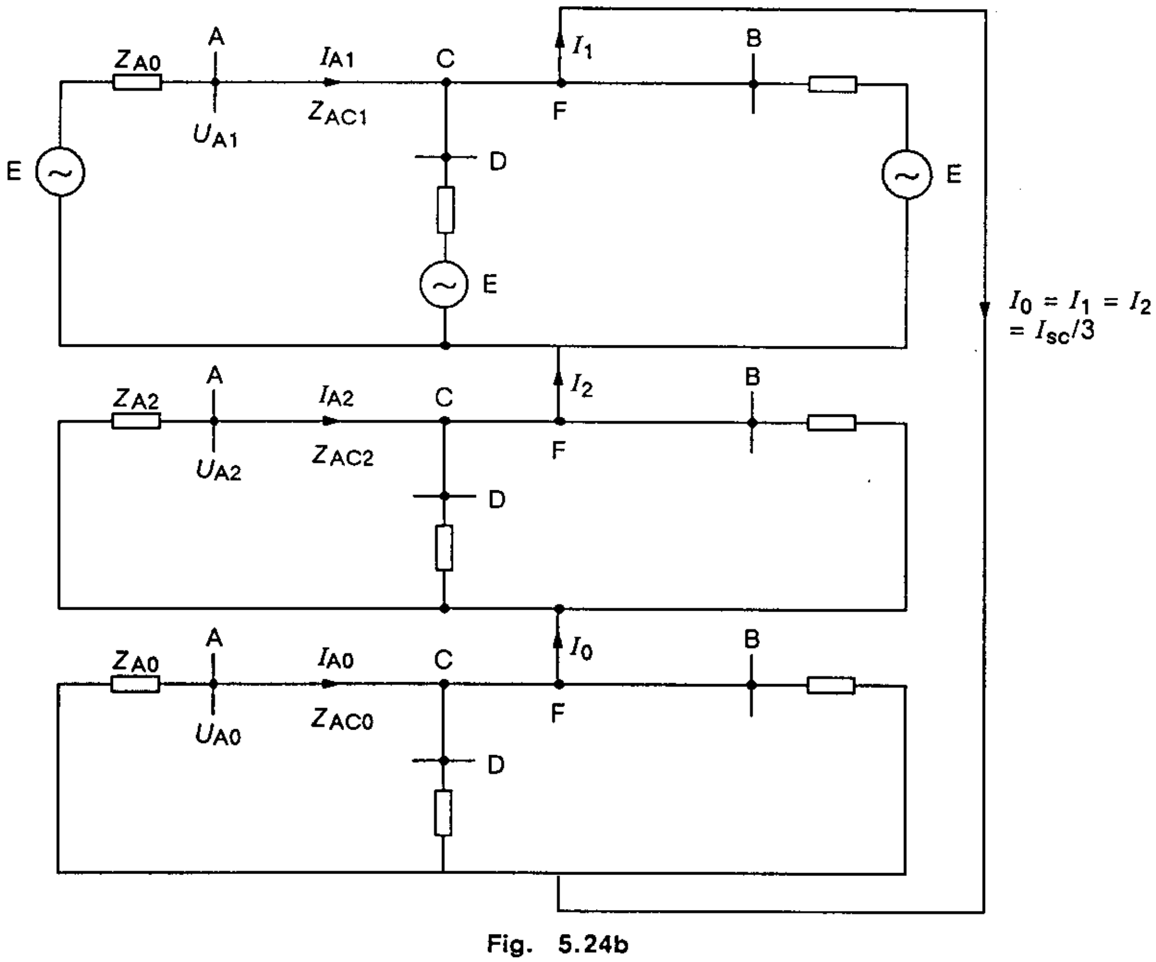



Fig. 5.24b

Consider for example the relay at A.

We have to calculate in this network the voltage $U_A$, the phase-current $I_A$ and the earth-current $I_{AE}$:

$U_A = U_{A0} + U_{A1} + U_{A2}$

$I_A = I_{A0} + I_{A1} + I_{A2}$

$I_{AE} = 3I_{A0}$

The measured impedance is: $Zm_A = \frac{U_A}{I_A + k_0 \cdot I_{AE}}$ ; $k_0 = \frac{Z_0 - Z_1}{3 \cdot Z_1}$

($Z_0$ and $Z_1$ are data of line A-B)

### 5.7.1.2 Outfeed conditions

This situation occurs if one terminal is much weaker than the other terminals, so that the fault current is flowing out of this terminal during an internal line fault:

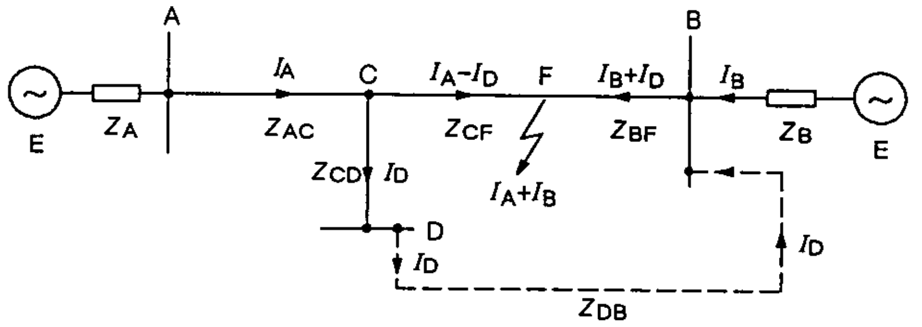



Fig. 5.25

$$U_A = I_A Z_{AC} + (I_A - I_D) Z_{CF} = E - Z_A I_A \qquad 13)$$
$$U_B = (I_B + I_D) Z_{BF} = E - Z_B I_B \qquad 14)$$
$$U_D = (I_A - I_D) Z_{CF} - I_D Z_{CD} = U_B + I_D Z_{DB} \qquad 15)$$

From these equations follows:

$$Z_{mA} = U_A / I_A = Z_{AC} + (1 - I_D/I_A) Z_{CF} \qquad 16)$$
$$Z_{mB} = U_B / (I_B + I_D) = Z_{BF} \qquad 17)$$
$$Z_{mD} = U_D / I_D = -Z_{CD} + (I_A/I_D - 1) Z_{CF} \qquad 18)$$

The underreach for the relay at A chanches into overreach because of the '– sign' in equation 16); the relay at D assumes a fault in reverse direction; the relay at B measures the correct distance.

If no telecommunication is provided the relays at A and B will trip first; after that the current at D will reverse and the relay at D will trip (sequential tripping).

If we use a permissive underreaching scheme, then it depends on the value of the current at D if this relay will detect the fault and will fast trip after having received signals from A and B. If not, sequential tripping will occur again.

A directional or phase comparison scheme will not operate correctly under outfeed conditions.

A differential scheme will probably be the best solution to protect three-terminal lines with possible outfeed situations. The summation of the currents at the terminals A, B and D will give a positive result, independent of the fault location on the three terminal line:

$$I_\Delta = |\Sigma I| = |I_A + (I_B + I_D) + (-I_D)| = |I_A + I_B| \qquad 19)$$

It should, however, be considered that under outfeed conditions the differential protection is more highly stabilized than under normal infeed conditions:

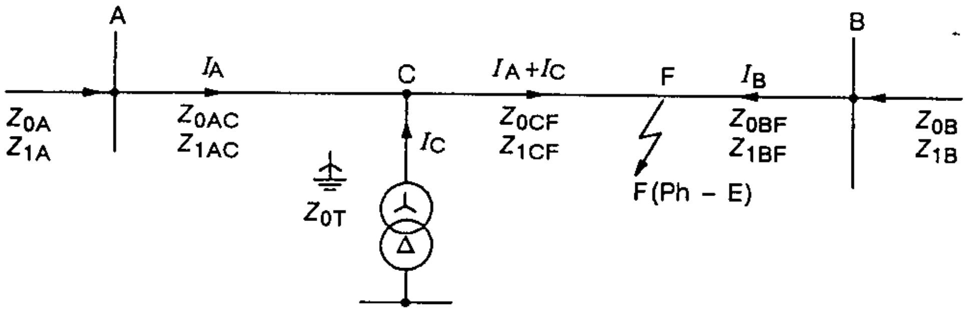
$$I_S = \Sigma |I| = |I_A| + |I_B + I_D| + |-I_D| = I_A + I_B + 2I_D \qquad \text{(compared to } I_A + I_B\text{)}$$

Distance relays as back-up protection remain necessary for the case that a telecommunication channel fails (unless there are two independent telecommunication channels).

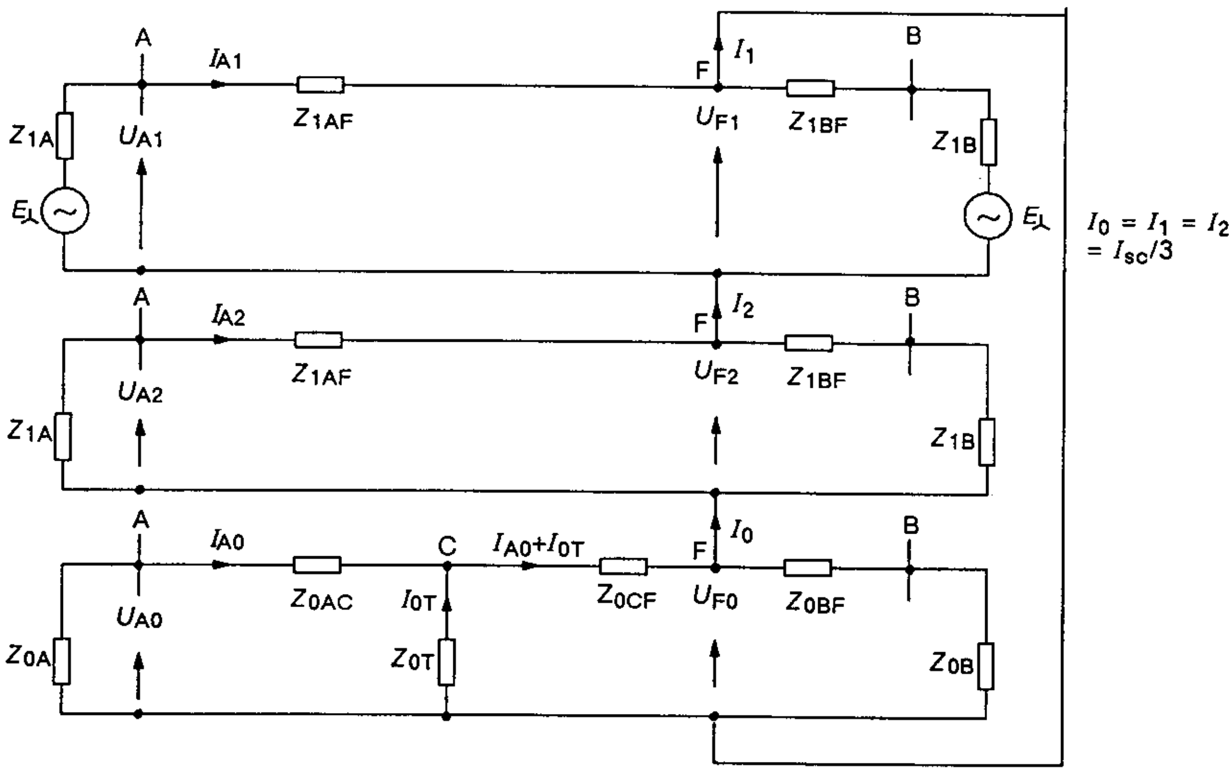
## 5.7.2 Tapped lines, distance zone reach problems

One of the main difficulties with the protection of tapped lines is dealing with single-phase-to-earth faults if the HV-neutral of the tapped transformer is earthed.

Take the next configuration:




a) Tapped line, single line diagram




b) Tapped line, diagram of symmetrical components

Fig. 5.26

$$U_{A0} = U_{F0} + Z_{0CF}(I_{A0} + I_{0T}) + Z_{0AC}\, I_{A0}$$
$$U_{A1} = U_{F1} + Z_{1AF}\, I_{A1}$$
$$U_{A2} = U_{F2} + Z_{1AF}\, I_{A2}$$

with $U_{F0} + U_{F1} + U_{F2} = 0$ and $Z_{0AC} + Z_{0CF} = Z_{0AF}$ we get:

$$U_A = Z_{0AF}\, I_{A0} + Z_{0CF}\, I_{0T} + Z_{1AF}(I_{A1} + I_{A2}) \qquad 20)$$
$$I_A = I_{A0} + I_{A1} + I_{A2} \qquad 21)$$

For the component-currents we get:

$$I_{A0} = \frac{Z_{0T}}{Z_{0T} + Z_{0A} + Z_{0AC}} \cdot \frac{Z_{0B} + Z_{0BF}}{Z_{0B} + Z_{0BF} + Z_{0CF} + \dfrac{Z_{0T}\,(Z_{0A} + Z_{0AC})}{Z_{0T} + Z_{0A} + Z_{0AC}}}\, I_0 \qquad 22)$$

$$I_{A1} = I_{A2} = \frac{Z_{1B} + Z_{1BF}}{Z_{1B} + Z_{1BF} + Z_{1A} + Z_{1AF}}\, I_0 \qquad 23)$$

The current $I_0 = I_1 = I_2$ at the fault location must be calculated by solving the series-connected sequence network. Take for example a tapped line configuration as follows:

- 110kV-line, $Z_1 = Z_2 = 0{,}3\Omega$/km, $Z_0 = 0.75\Omega$/km, $k_0 = 0.5$, line length 30km;
- Transformer, 60MVA, UK = 10%, $Z_{0T} = Z_{1T} = Z_{2T} = 20\Omega$, tapped 10km from A;
- Sources of 500 and 1000MVA
  $Z_{0A} = Z_{1A} = Z_{2A} = 25\Omega$
  $Z_{0B} = Z_{1B} = Z_{2B} = 12.5\Omega$
- A single phase fault occurs at line A-B, 20km from A and 10 km from B:

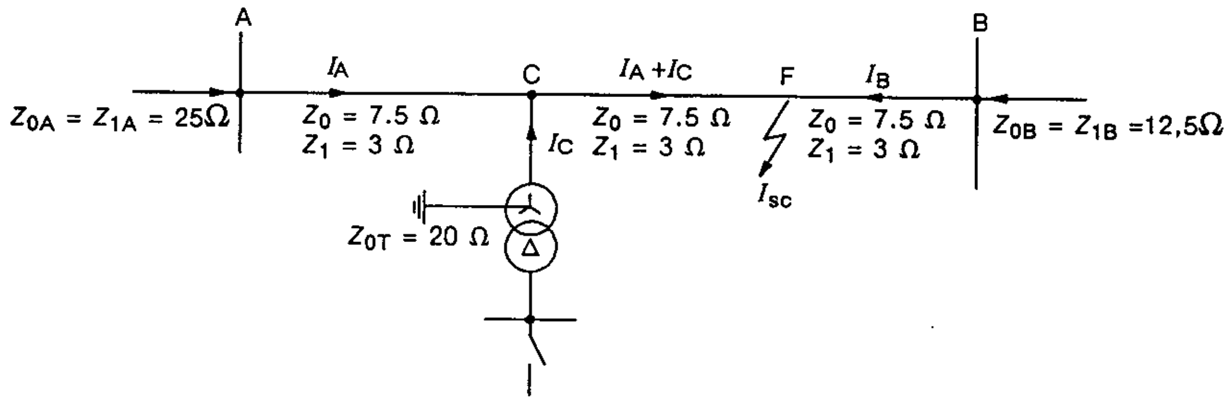



Fig. 5.27

| | | | | |
|---|---|---|---|---|
| $Z_{0F}$ | $= 10\Omega$ | | | |
| $Z_{1F}$ | $= Z_{2F}$ | $= 10.3\Omega$ | | |
| $I_0$ | $= I_1$ | $= I_2 = 110\text{kV}/\sqrt{3}(10 + 2 \cdot 10.3)\Omega = 2.1\text{kA}$ | | |
| $I_{sc}$ | $= I_0 + I_1 + I_2 =$ | 6.3 kA | | |
| $I_{A0}+I_{0T}$ | $= 0.5\, I_0$ | $= 1.05$kA | | |
| $I_{A0}$ | = 0.4kA; $I_{0T}$ = 0,65kA; $I_{AE} = 3 \cdot I_{A0}$ | | = 1.2kA | 22) |
| $I_{A1}$ | $= I_{A2}$ | $= 0.33\, I_0$ | = 0.7 kA | 23) |
| $U_A$ | = 15Ω•0.4kA + 7.5Ω•0.65kA + 6Ω•1,4kA | | = 19.3kV | 20) |
| $I_A$ | = 0.4kA + 2•0.7kA | | = 1.8kA | 21) |
| $Z_{mA}$ | $= U_A/(I_A + k_0 \cdot I_{AE})$ | | = 19.3kV/(1.8kA + 0.5 · 1.2kA) = 8Ω | |

Positive sequence fault impedance $Z_{1AF} = 6\Omega$.

Error = 2Ω: the apparent fault location is 6.7 km farther away than the real fault location.

The underreach in this example is about 33%. By repeating the calculation with different fault locations and varying source strengths, we can find an optimal setting for the relays at A and B for single-phase-to-earth faults.

# 6 Protection of composite lines

## 6.1 Introduction

In a larger number of cases power system elements like transformers, overhead lines or cables are connected together without intermediate circuit-breakers. In many cases CTs or even VTs are provided at the junction points to enable the setup of independent protection schemes for the different sections. Fault clearance, however, requires always the tripping of the complete composite line.

## 6.2 Protection problems encountered

The normal origin of difficulties is this lack of circuit breakers between the protected elements and the current or voltage transformers at the needed locations:

- Autoreclosure is wanted for OH-lines but must be prevented under all conditions for faults on cables or transformers
- The absence of CTs or VTs may necessitate grading distance zones across transformers. The transformation of fault impedances from the fault- to the relay-side in magnitude and phase-angle has then to be considered.
- Remote breakers have to be intertripped with minimal expenditure for signalling-links.
- Transformer inrush currents may adversely affect the line protection of transformer feeders.

## 6.3 Protection of a composite OHL-cable feeder

This arrangement appears relatively often, either when an overhead line is conducted into a substation or when certain obstacles in the landscape (river, channel etc.) have to be passed.

Such composite OHL-cable combinations normally provide no problems for the selection and layout of the protection. Only in connection with autoreclosing (AR) special provisions are necessary.

Selective AR has to be ensured, i.e. AR is normally only allowed with OHL faults. Cable faults are not transient and therefore require definite tripping and blocking of the AR.

This is achieved by providing a separate selective cable protection that sends blocking signals to the AR-schemes at both line ends when the fault occurs at the cable section.

Current differential protection or PCP are suitable for this purpose, as they are strictly selective and, additionally, do not require VTs (fig. 6.1).

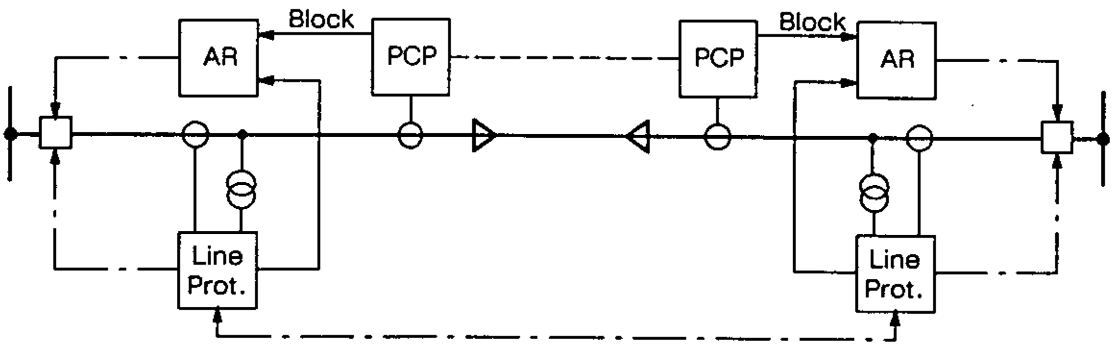



**Fig. 6.1: Protection of a composite OHL-cable feeder**

## 6.4 Protection of transformer feeders

In cases where a line includes a transformer bank without a breaker inbetween, both have to be protected as a unit.

The selection of the protective equipment for such composite arrangements depends mainly on the following conditions:

- Length of the feeder (OHL or cable)
- Availability of CTs and VTs on the line side of the transformer bank
- Availability of pilot links:
  - for differential protection
  - for command protection systems with distance protection
  - for intertripping

While it is always necessary to trip the transformer-line system as a whole for faults on either or both components, it is normally preferred to set up independent protection schemes that can selectively indicate the fault location in the transformer or on the line section.

### 6.4.1 Transformer protection

The transformer bank is normally equipped with sensitive differential protection and gas pressure relays. They trip the local bus breaker directly and the remote line breaker via an intertripping link. The latter is necessary because light internal transformer faults will probably not produce enough current increase or voltage drop to operate the short circuit protection, e.g. distance relay, at the remote line end

The following possibilities exist:

- **d.c. intertripping via pilot wires:**

  Special surge-proof relays are used at the receiving end, insensitive to a.c.-disturbances [5]. The application of these d.c. links is limited to short distances of up to about 5 km.

- **a.c. intertripping:**

  Frequency shift or coded voice frequency channels, directly on pilot wires, or carrier frequency systems are used for this purpose.

- **unbalancing the line differential protection:**

  Some line differential protection schemes provide an integrated intertripping function by a forced unbalancing of the measuring system or the supplementary voice frequency circuit that normally serves for pilot supervision.

- **fault throwing:**

  In some cases fault-throwing switches are used on lower voltage levels to save transmission channels. A special switch is used to put a fault on the line side of the transformer bank, initiated by the local protection. The remote end short circuit protection will then see the fault and trip its line circuit breaker.

### 6.4.2 Protection of the line section

The line section can be protected by an independent line differential protection when CTs are provided between transformer and line. This is normal, especially in the case of transformer-cable feeders (fig. 6.2).

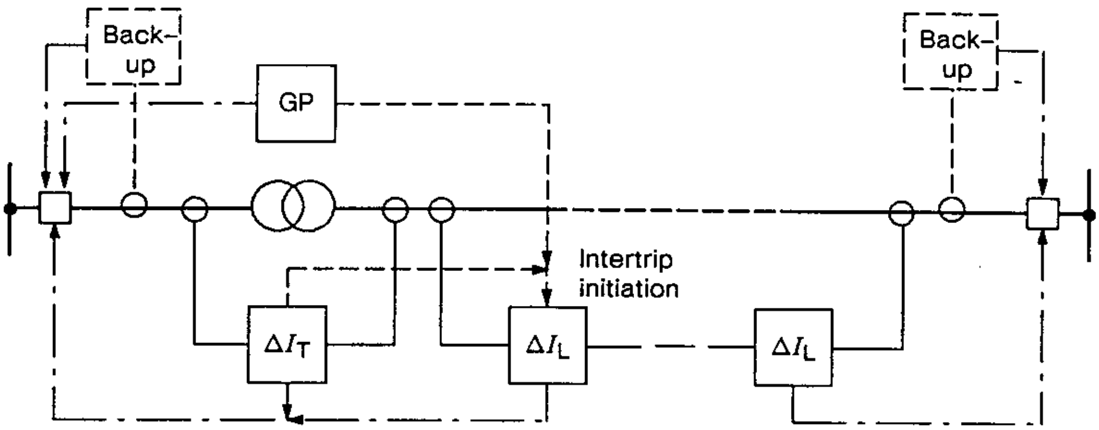



**Fig. 6.2: Selective differential protection of a transformer feeder**

### 6.4.3 Overall differential protection of a transformer feeder

In the case of very short line sections (below about 1km), an overall differential protection can be used as a cost saving solution when no CTs are provided between transformer and line. The differential protection must be inrush-stabilized in this case, as the transformer bank lies within the protection range. A transformer differential relay can be applied as outlined in fig. 6.3.

The current in the pilot wires can be reduced via intermediate auxiliary CTs (e.g. to 100mA) to lower the CT burdens.

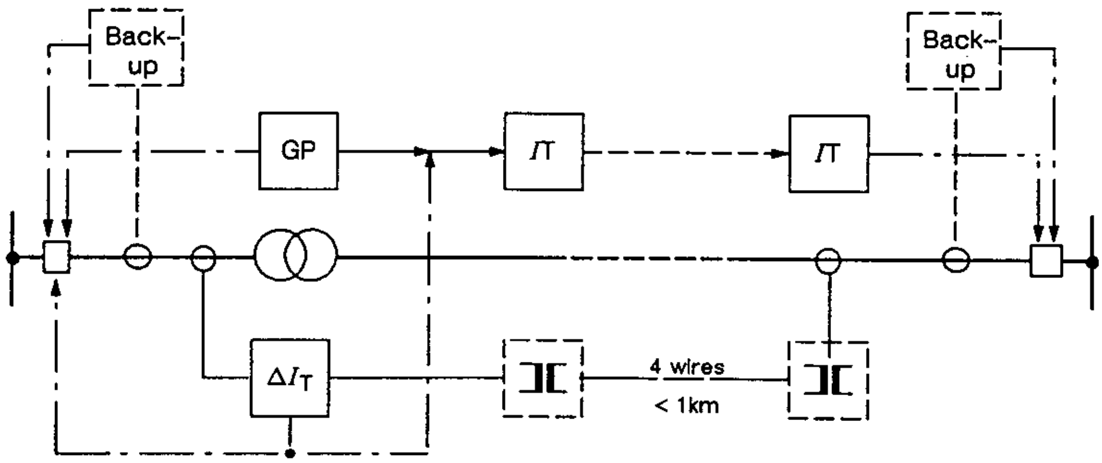



**Fig. 6.3: Transformer feeder, overall differential protection**

### 6.4.4 Distance protection of the transformer feeder

At the transformer remote line end the instaneous zone of the distance relay can be set to reach about 50% into the transformer, thus covering 100% of the line section.

Normal zone grading is possible for the distance relay at the transformer bank when it can be connected to CTs and VTs at the line side (fig. 6.4). This latter protection can be spared if there is no infeed from terminal A.

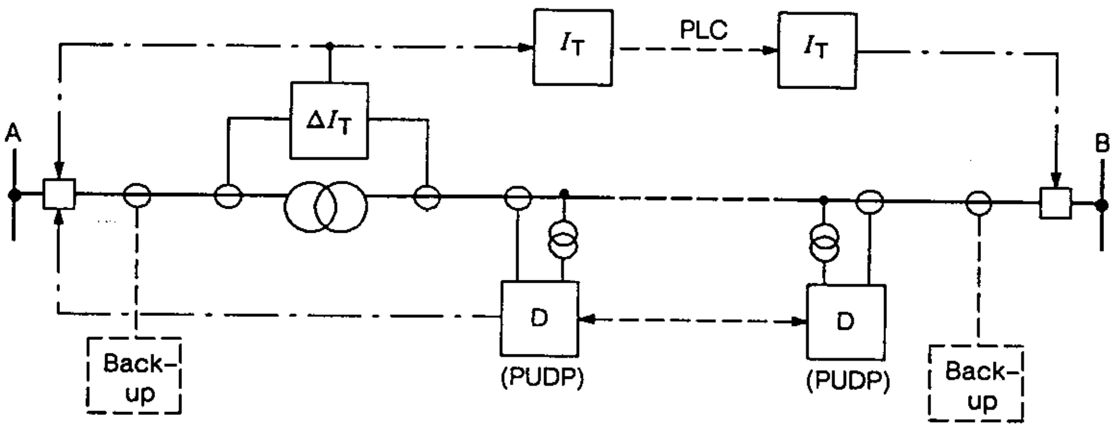
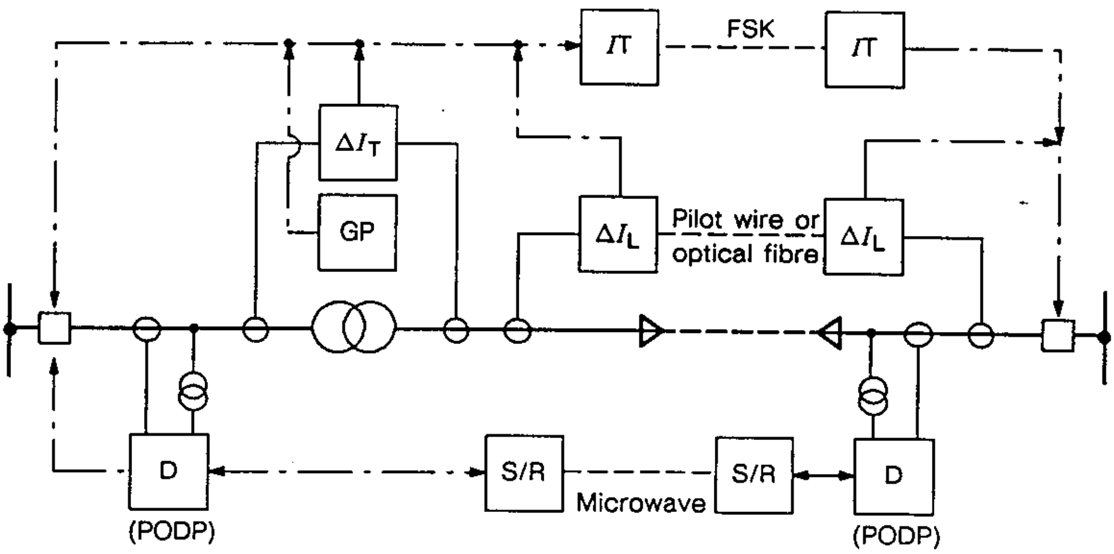



**Fig. 6.4: Transformer feeder, protection of the line section**

In the case, where the distance relay has to be connected to the bus-side CTs and VTs, the distance measurement includes the impedance of the transformer bank.

A correct distance measurement through the transformer bank is possible with three-phase faults. But, the setting of a selective underreaching zone can only be achieved when the line reactance is considerable higher than the transformer reactance ($X_L > 2 \cdot X_{TR}$) [12]. Further, the impact of the tapchanger has to be considered.

The reach of the underreaching zone must be adjusted to about 90% of the minimum secondary ohms while the overreaching zones must at least cover 100% of the maximum secondary ohms according to the variation range of the tap changer (fig. 6.5).




$$Z_{1st\ zone} < Z_{Tr} + 0.9\ \left(\frac{U_1}{U_2}\right)^2_{min} \cdot Z_L$$

$$Z_{2nd\ zone} > Z_{Tr} + \left(\frac{U_1}{U_2}\right)^2_{max} \cdot Z_L$$

**Fig. 6.5: Transformer feeder, impact of the tap changer on the zone setting**

Further problems are presented by unsymmetrical faults and earth faults on the line section. The fault-currents, -voltages, and -impedances on the bus-side of the transformer bank are influenced by the winding connections (Y-Y,Y-Δ, etc.) and the earthing conditions of the transformer starpoint(s) [6.5].

Normally, this would lead to an underreach of the zones and delayed clearance of faults on the line section.

When fast tripping for all kind of faults on the transformer feeder has to be guaranteed, the distance protection must be supplemented by a teleprotection scheme. The usual permissive under- or overreaching, or blocking modes can be applied.

The energizing of the transformer feeder will cause the typical inrush effect with transient magnetizing currents. The setting of the distance relay should take care of the fact, i.e. the starting elements should not be set more sensitive than necessary.

### 6.4.5 Application examples

In the following the protection system for two typical application cases are shown.

#### 6.4.5.1 Transformer-OHL feeder protection

In this case it is assumed that the line section is longer than about 15km and that, therefore, pilot wire differential protection cannot be applied.

The **primary protection system** consists of (fig. 6.6):

- Transformer differential and gas pressure protection
- Optionally phase comparison protection (PCP) or fibre optic differential protection (FODP)

The PCP can have ($I_1$–, $I_2$– and $I_0$–) over-current or rate-of-change of current starting elements. As the PCP measuring principle is also based on currents only, there are no VTs necessary at the line-side of the transformer bank.

The PCP and the intertrip function can use PLC, microwave or optical fibre channels.

The secondary protection can be a permissive underreach distance protection scheme (PUDP). The underreaching distance zone can be set to overlap sufficiently.

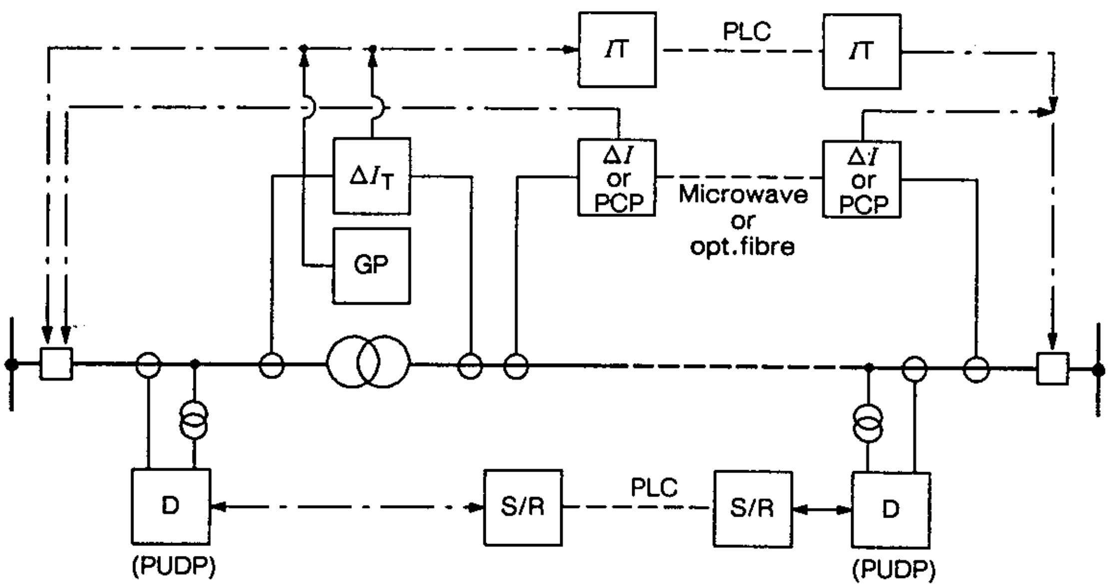



**Fig. 6.6: Protection of a transformer feeder with long OH-line section**

### 6.4.5.2 Transformer-cable feeder protection

In this case, it is assumed that the cable section is below 10-15km, so that a pilot wire differential protection can be applied. However, it is further assumed that the cable is longer than about 5km.

Thus, d.c. intertripping is not applicable, but, an a.c. channel (for example frequency shift channel through pilot wires) is necessary to cover reliably the given signal transmission distance.

The proposed scheme now consists of the following protection systems (fig. 6.7):

- **Primary protection:**
  - transformer differential and gas pressure relays
  - line pilot differential protection
  - frequency shift (FSK) intertripping equipment
- **Secondary protection:**
  - permissive overreaching distance protection (PODP) via Microwave

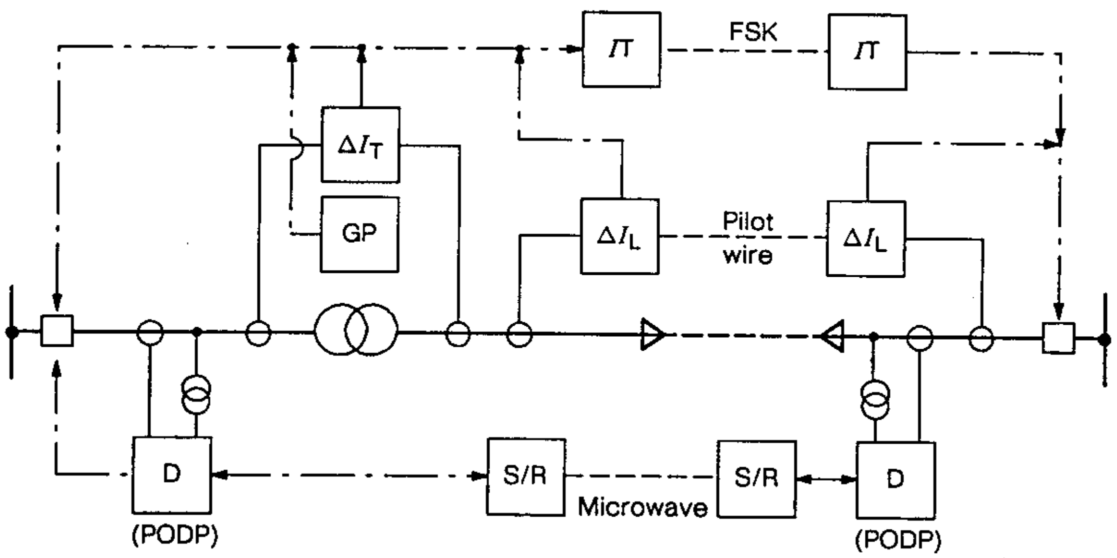



**Fig. 6.7: Protection of a transformer feeder with short cable section**

# 7 Protection of series compensated lines

## 7.1 Introduction

### 7.1.1 Advantages and disadvantages using series-compensation

The very first series capacitor was commissioned on a high voltage power line about forty years ago. The main purpose for using series capacitors is to decrease the resulting reactance of the transmission system and, consequently, to increase its transmission capacity. The cost compared with building a new equivalent overhead power line in this case was in order of 15-30%.

It is still economical to use series capacitors, particularly if there is a long distance from a generation to a consuming centre.

Series capacitors can also be used to regulate the power flow in the network by switching them in and out. Increasing transmission capacity sometimes also improves the stability of the network. A series capacitor also helps to keep the voltage on a good level at the receiving end of the power line, and it can sometimes replace shunt-capacitors or be a supplement to shunt compensation.

A capacitor bank consists of small capacitor elements connected together in series and parallel to form a large bank with high capacitance and high rated load current. The elements are sensitive to overvoltages and their lifetime is short compared with the power line itself. So the capacitor must be taken out for maintenance more frequently than for instance the power line.

A capacitor in a power network very often creates resonance phenomena of a subsynchronous nature with different kinds of inductive equipment.

The series capacitor also creates many additional protection problems compared with power line protection without capacitors [7.5, 7.18].

### 7.1.2 Locations

Often there is only one capacitor bank on a power line, but sometimes the compensation is divided into two or more banks at different locations (mid-line capacitors). Very often there is one bank at each end of the power line (line-end capacitors).

Dividing the compensation between different locations gives a smoother voltage profile over the whole power line. If the capacitor is placed in the middle of the line or split up and placed at the ends of the power line, it usually gives the smallest voltage discrepancy when the direction of reactive power-flow changes.

If there is only one direction of the reactive power flow it can be an advantage to place the capacitor at the receiving end of the power line in order to get a good voltage level at this end.

The capacitor can hardly be designed to withstand overvoltages which occur when there is a fault on the power system and a high fault current is passing through the capacitor. Capacitors are therefore protected against overvoltage by an airgap and sometimes nowadays also with a non-linear resistor. It is an advantage to locate the capacitor so that the airgap will not flash when a fault occurs outside of the power line, particularly on a parallel circuit. To lose the compensation at the same time as a parallel line is disconnected is a very difficult situation for the power system.

However, when the capacitor is located close to one end of the power line it is impossible to fulfil this requirement because the primary task of the airgap is to protect the series capacitor against high voltage. Some auto-opening scheme for the bypass-circuit-breaker is usually installed for quickly reinserting the capacitor in the network. A resistor protected capacitor gives some advantages in this case because the whole compensation will not be lost when part of the fault current is going through the resistor; see fig. 7.1 and 7.2.

Placing capacitors near a substation gives advantages in maintainance and operation because the series capacitor becomes a part of the substation.

If the series capacitor is located far away from substations it must be remotely controlled and is only attended occasionally or during maintenance.

### 7.1.3 Compensation degree

The ratio of the capacitor reactance to the reactance of the power line is called the compensation degree k, see 7.1:

$$k = X_C / (X_{11} + X_{12}) = X_C/X_L$$

A compensation degree below 40–50% and the location in the middle of the line usually gives no problem for the line protection.

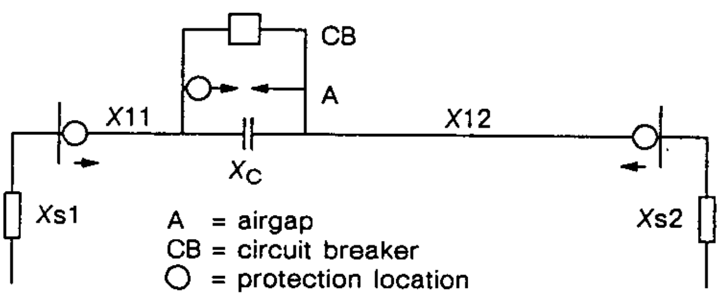



**Fig. 7.1: Conventional airgap-protected capacitor**

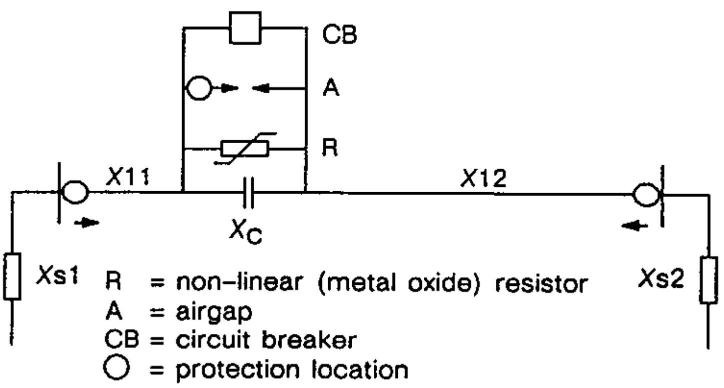



**Fig. 7.2: Resistor-airgap-protected capacitor**

## 7.2 Protection problems encountered

Series capacitors have a strong impact on line protection as a consequence of the following phenomena:

- Negative lumped reactance of the series capacitor connected in series with a distributed positive line reactance.
- Changing of the apparent impedances dependent on the capacitor protection gaps having flashed or not.
- Voltage or current inversion when the short circuit impedances assume negative values.
- Subsynchronous oscillations in the L–C–R circuit composed of the series capacitor and the source and line impedances.
- Dissymmetries due to nonsymmetric gap flash–over/reinsertion and reinsertion and amplification of the existing dissymmetries of non–transposed lines cause circulating negative sequence currents.
- Slow increase of the short circuit current in the L–C–R fault loop as a consequence of a superimposed subsynchronous transient component.

### 7.2.1 Apparent impedances

The following figures show the impedances appearing to a distance relay located at station A.

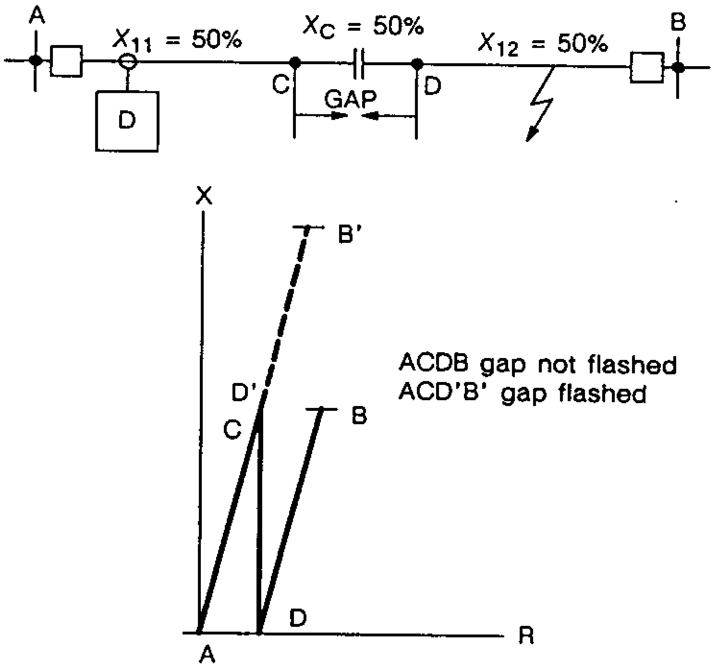



**Fig. 7.3: Apparent impedances of a series compensated line (capacitor at the middle of the line)**

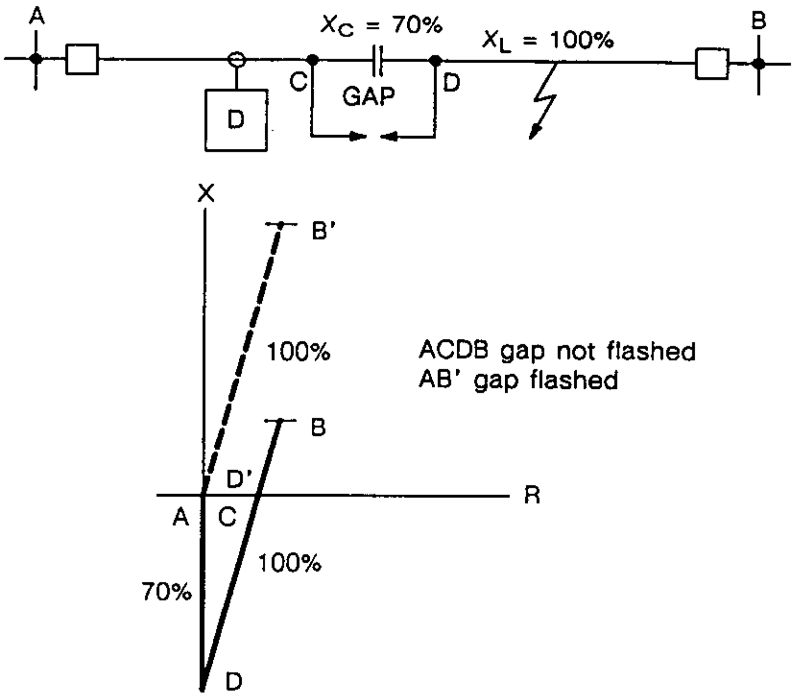



Fig. 7.4: **Apparent impedances of a series compensated line (capacitor at the beginning of the line and VT at point C)**

The figures demonstrate the measuring problems for distance relays:

- Faults beyond the series capacitor appear closer when the capacitor is in service, i.e. distance protection underreaching zones must be set very short to avoid overreach.
- Forward faults may appear to the distance relay in reverse direction (fig. 7.4).
  Conventional faulty-phase polarized directional measurement detects the fault in the wrong (reverse) direction.
  Healthy phase- and memory voltage polarisation must be taken into account.

### 7.2.2 Voltage inversion (Negative voltage)

The following figure 7.5 shows the voltage distribution for the normal service case and for a fault behind the series capacitor (assumed that the gaps have not flashed over). It can be seen that the measured voltage at the relay location is inverted. This causes the before mentioned false decision of directional relays.

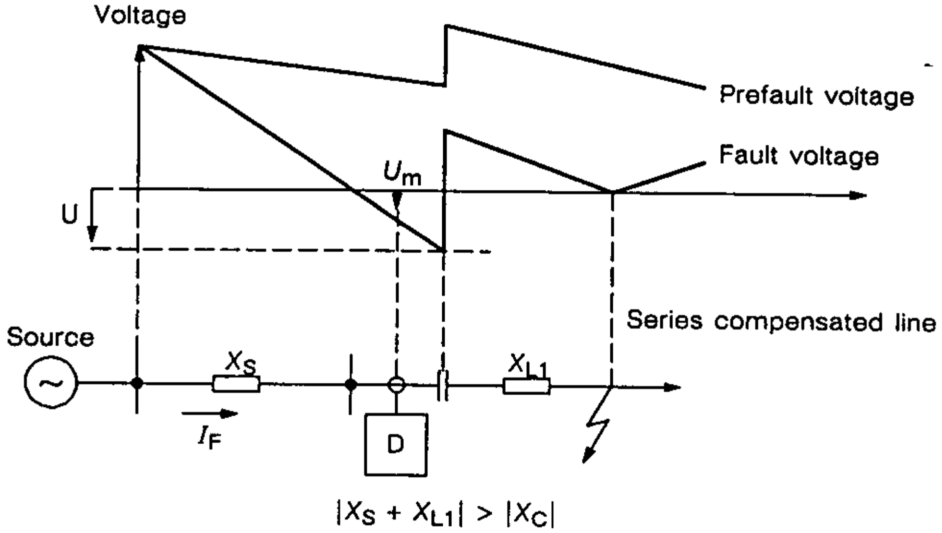



**Fig. 7.5: Voltage inversion at a series compensated line**

### 7.2.3 Current inversion (Negative current)

This situation can occur when the amount of the negative reactance of the series capacitor is more than the sum of the positive source- and line-reactances in the total fault loop.

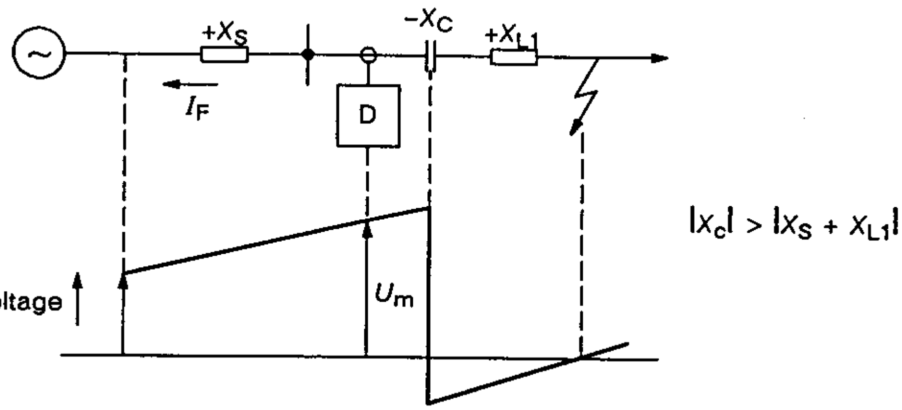



**Fig. 7.6: Current inversion on a series compensated line**

The short circuit current then becomes 'capacitive', that is, the current leads the voltage phase. This again causes a false directional decision of distance relays (voltage memories can not help in this case!). Also phase comparison relays may fail because the current from the other line end to the fault remains normally inductive. Thus, a through-fault condition appears to the PCP for an internal fault. Fortunately, the capacitive current causes a voltage increase on the transmission system and the gaps will normally flash as the short circuit current is high due to the series compensation. In the normal case the protection must therefore not cover this abnormal fault condition [7.17, 7.15].

### 7.2.4 Subsynchronous oscillations and transients

During the fault-free service, subsynchronous oscillations may be excited in the L-C series connected network elements. Generators tend to self-excitation in this case and the turbine-generator shaft may be torsionally endangered [7.5, 7.17].

Under short circuit conditions a special effect occurs: The short circuit loop is no more an L-R circuit that is accompanied by a d.c.-transient component, but an L-C-R circuit, where instead of the d.c. offset a low frequency transient current oscillation appears. This leads to a slow current increase dependent on the degree of compensation (see section 7.12).

The superimposed oscillation of the order of 20Hz also causes a fluctuation of the impedance measured by the relay dependent on the individual relay filtering properties.

## 7.3. Protection of the series capacitor

### 7.3.1 General

A series-capacitor station can be divided into two or three segments, all connected in series (fig. 7.7). Each segment has its own airgap with by-pass circuit-breaker and its own protection. This is an advantage when one segment is faulty because then the whole capacitor bank will not be tripped and lost. In some cases the layout of the station is designed so that maintenance work can be done at one segment while the others are in operation.

The airgap for each phase operates independently of the other two phases, but the circuit-breakers in the capacitor station usually operate in a three-pole mode.

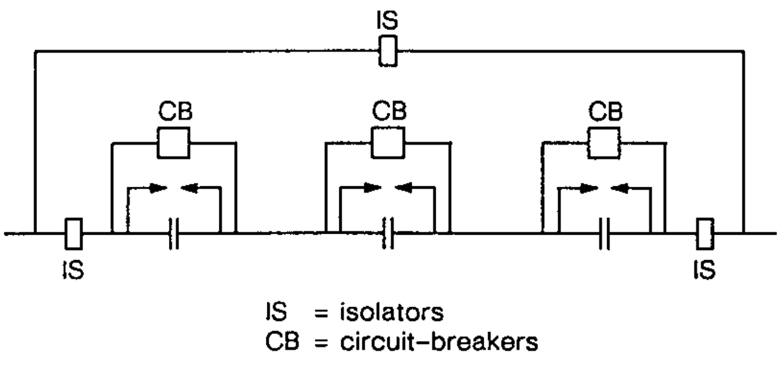



**Fig. 7.7: A series-capacitor divided into three segments**

### 7.3.2 Protection of a conventional airgap-protected capacitor

A conventional airgap-protected capacitor needs many protection functions. The most common types are described in the following and shown in figure 7.8.

The most important protection is the airgap. It has to protect the capacitor from overvoltages. The capacitor is designed for a certain rated voltage and, consequently, a corresponding rated current (IEC43). The capacitor can usually stand just a few percent overvoltage for a short time. A high fault current passing through the capacitor creates high voltage, and the capacitor is normally not designed to withstand the highest existing fault current. An airgap will flash for a voltage lower than the withstand capability of the capacitor. The setting of the airgap depends upon the design of the capacitor. A common setting is 2-3 times the rated voltage.

Normally the fault current in the airgap is interrupted after 0.1s by the power line circuit-breaker initiated from the line protection. The airgap is usually not able to withstand the fault current for very long periods. An overcurrent protection, placed in series with the airgap, must short the airgap by means of a circuit-breaker so the airgap can be deionised. If the fault clearing by the line protection is delayed for some reason, this overcurrent protection will operate in the order of 0.4s. If the gap can flash for external faults, this protection is instantanous.

The capacitor bank is usually placed on a platform insulated from ground. Sometimes one or two segments can be placed on one platform. In the event of a flashover from the capacitor to the platform, a leakage protection will operate instantanously and the capacitor banks will be shorted.

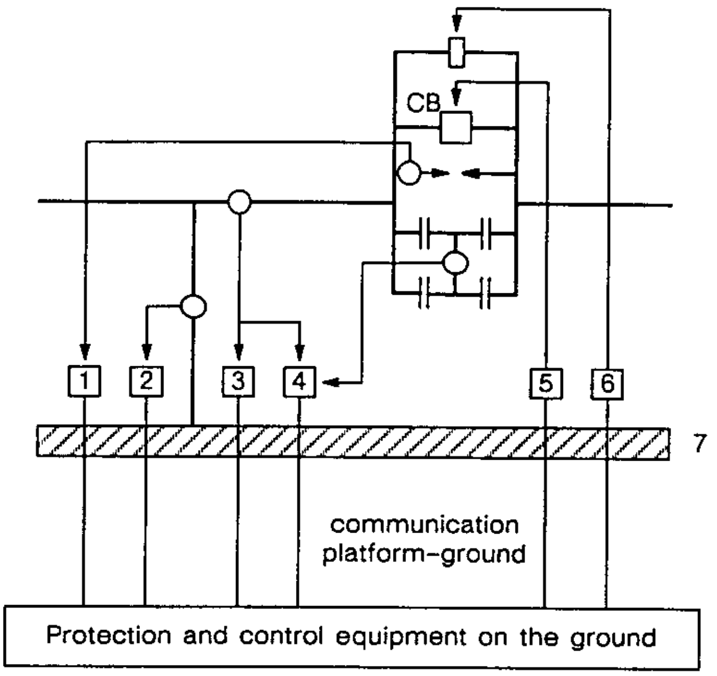
In order to detect faulty elements in the capacitor, unbalance protection is installed. This compares the voltages of the capacitor elements in a bridge circuit. The protection sometimes consists of two stages, one high set and one low set. The low set may be restrained by the load current, both are slightly delayed to avoid maloperation from transients during switching.

Capacitors in power systems can cause resonance phenomena. A protection detecting ferro-resonance is sometimes installed and nowadays also a protection detecting resonance between the capacitor and the large turbo generator's torsional oscillation is also installed if network studies have shown that there is a probability of such phenomena. Ferro-resonance is more frequently encountered in low and medium voltage networks.

If the circuit-breaker fails to short a capacitor segment, a disconnector will short the whole capacitor bank.

Usually all capacitor protection operates without any telecommunication with the power line protection at the ends of the power line. Protection and control equipment placed on the ground requires a lot of information from the platform. Nowadays optical fibres are used as communication media.

If the circuit-breaker fails to short the capacitor, an isolator switch will short the circuit-breaker and the capacitor (a few seconds later). Sometimes the breaker-failure function will intertrip the circuit-breakers at the power line ends.




1 Over-current protection, detecting current in the airgap
2 Leakage protection, detecting flashover between the capacitor and the platform
3 Subsynchronous resonance protection
4 Unbalance protection, detecting broken elements in the capacitor
5 Control of the circuit breaker
6 Circuit-breaker failure protection
7 Platform isolated from ground

**Fig. 7.8: Protection in a conventional airgap protected capacitor station**

### 7.3.3 Protection of a resistor-airgap-protected capacitor

As stated earlier, a new overvoltage protection for capacitors has been developed. It consists of a non-linear resistor (metal-oxide-resistor), placed in parallel with the capacitor (fig. 7.9).

When the voltage across the capacitor rises, the resistance will become less and a great deal of the fault current will pass through the resistor instead of the capacitor. The airgap is set to flash only for extremely high voltages, which normally only occur when the faults are very close to the capacitor and the gaps are set to avoid flash-over for external faults. The energy developed in the resistor will be measured, and if it has reached the thermal limit of the resistor, a command is given to the airgap to flash. This scheme keeps at least a part of the compensation in service during a fault on an adjacent power line. When the fault is cleared the compensation comes immediately back into operation.

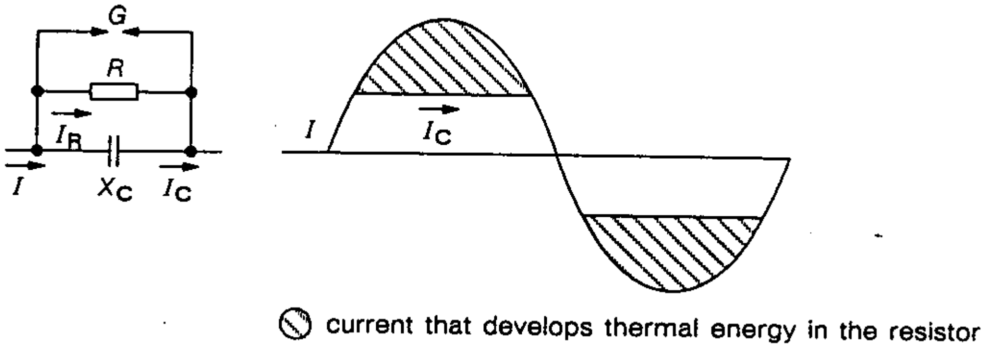
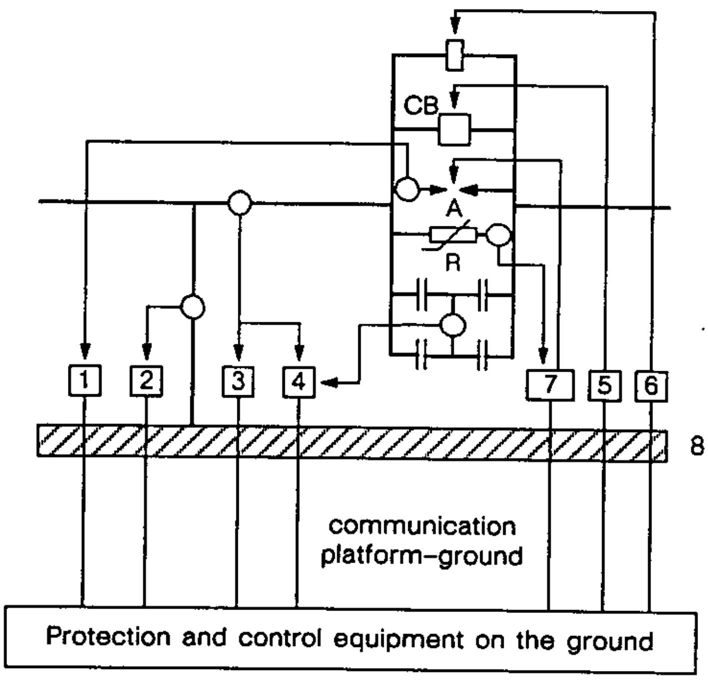



**Fig. 7.9: Resistor-airgap-protected capacitor**

Figure 7.10 shows the most common protection of a resistor-airgap protected capacitor, which is almost the same as in a conventionally protected capacitor.




1 Over-current protection, detecting current in the airgap
2 Leakage protection, detecting flashover between the capacitor and platform
3 Subharmonic protection, detecting subsynchronous resonance
4 Unbalance protection, detecting failure in elements of the capacitor
5 Control of the circuit-breaker
6 Circuit-breaker failure protection
7 Protection, detecting developed energy in the non-linear resistor
8 Platform isolated from the ground

**Fig. 7.10: Protection in a resistor-airgap-protected capacitor station**

## 7.4 Power line protection based on non-unit principles

Series-compensated power lines are often very important in a transmission network and delayed fault clearance is normally not allowed. This makes it necessary to install protection in combination with telecommunication. The most common protection is distance protection in a permissive overreach mode.

Most protection problems in series-compensated lines appear when using distance protection. For that reason it seems to be a good start to analyse problems concerning ordinary distance protection and to try to find out how protection with other principles or modified distance protection can cope with these problems.

### 7.4.1 Distance protection

#### 7.4.1.1 Underreaching and overreaching schemes

In order to obtain section selectivity, the first zone of a distance protection must be set to a reach less than the reactance of the compensated line in accordance with figure 7.11. Very often it is set to

$$\text{zone } 1 = 0.85 \times [X11 + X12 - Xc]$$

The setting is usually the same if the capacitor is protected by a conventional airgap or a resistor-airgap.

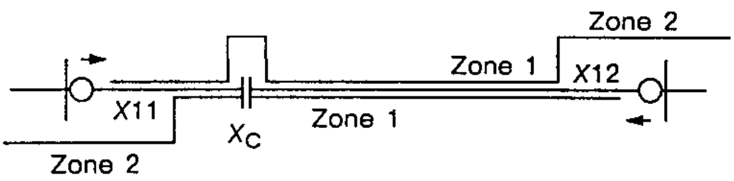
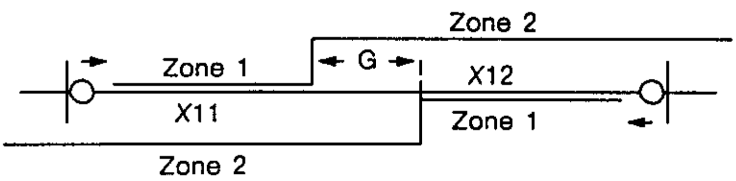



**Fig. 7.11: Setting of the first and second zones in series-compensated lines**

If the capacitor is shorted or is out of service, the reach with these settings can be less than 50% depending on the compensation degree and there will be a section, G in figure 7.12 of the power line where no instantanous tripping occurs from either end.




Zone 1 = 0.85x ($X11 + X12 - X_C$)

Zone 2 = 1.3x ($X11 + X12$)

G = gap, where no instantanous tripping can occur. The capacitor is shorted.

**Fig. 7.12: The reach of the first and second zones after the capacitor is shorted**

For that reason permissive underreaching schemes can hardly be used as a main protection. Permissive overreaching distance protection or some kind of directional or unit protection must be used.

The overreach must be of an order so it overreaches when the capacitor is out of service. Figure 7.13 shows the overreach zone A. The first zone can be kept in the total protection but it has only the feature of a back up protection for close up faults. The overreach is usually of the same order as zone 2. When the capacitor is in operation zone A and zone 2 will have a very high degree of overreach which can be considered as a disadvantage from the security point of view.

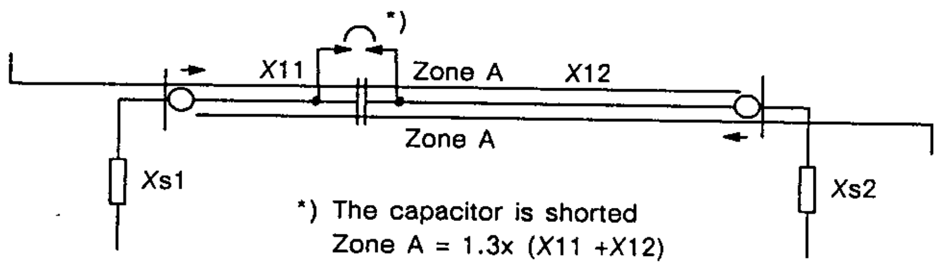



Fig. 7.13: Permissive overreach distance protection

### 7.4.1.2 Negative relay impedance, positive fault current

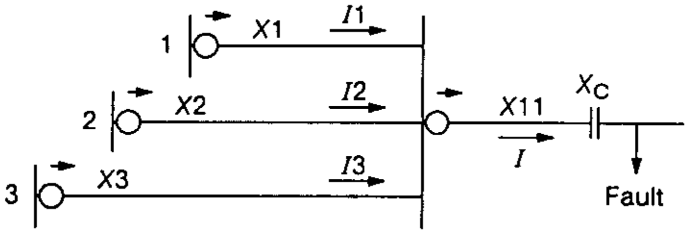
Assume [Xc] > [X11] and in figure 7.14 a three phase fault occurs beyond the capacitor. The resultant relay-impedance seen from the relay location to the fault becomes negative until the airgap has flashed.

It usually takes a bit of a time before the airgap flashes, and sometimes the fault current will be of such a magnitude that there will not be any flash-over and the negative impedance will be sustained. If [Xs1 + X11] > [Xc] in figure 7.15, the fault current will have the same direction as when the capacitor is shorted. So, the directional measurement is correct but the impedance measured is negative and if the characteristic crosses the origin shown in figure 7.15 the relay cannot operate. However if there is a memory circuit and this one has been given a design so it covers the negative impedance one can be successful to clear a three phase fault with the distance protection. As soon as the airgap has flashed the situation for protection will be as for an ordinary fault. However, a good protection system should be able to operate correctly before and after flashing as well.

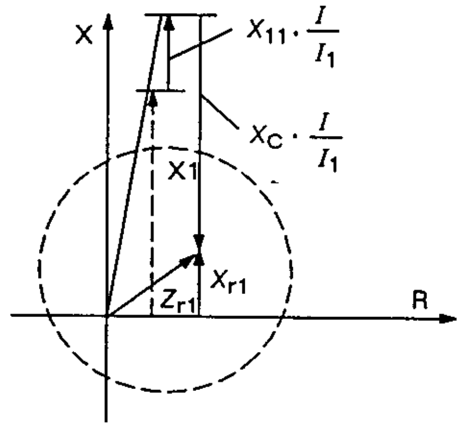
If the distance protection is equipped with an earth fault measuring unit, the negative impedance occurs when $[3Xc] > [2X11_1 + X11_0]$. Crosspolarised distance protection will normally handle earth faults satisfactorily if the negative impedance occurs inside the characteristic. The operating area for negative impedance depends upon the magnitude of the source impedance and calculations must be made from case to case. See figure 7.16 and 7.17.

Distance protections of adjacent power lines shown in figure 7.14 are influenced by this negative impedance. If the intermediate infeed of short circuit power by other lines is taken into consideration, the negative voltage drop at $X_C$ is amplified and a protection far away from the faulty line can maloperate by its instantaneous operating distance zone if no precaution is taken. Normally the first zone of this protection must be delayed until the flash over has taken place. If the delay is not acceptable, some directional comparison must also be added to the protection of all adjacent power lines. As stated above a good protection system must be able to operate correctly both before and after flashing. A distance protection can be used, but careful studies must be made for each individual case.

What is said here is valid both for conventional airgap and resistor-airgap-protected capacitors.




Assume [$X_C$] > [$X11$]
$Xr1 = X1 - I/I1 \times (X_C - X11)$
$Xr2 = X2 - I/I2 \times (X_C - X11)$
$Xr3 = X3 - I/I3 \times (X_C - X11)$
$I1 + I2 + I3 = I$
$Xr$ = measured relay reactance




Reactance $X_{r1}$, seen by the relay in station 1

**Fig. 7.14: Protections in adjacent power lines are influenced by the neg. impedance**

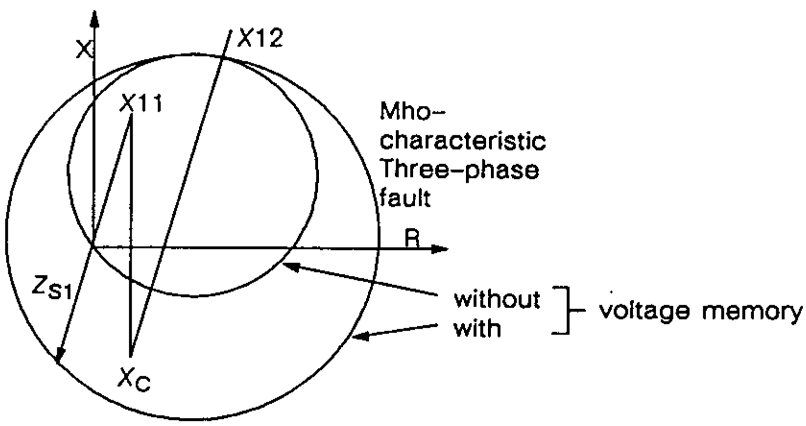



**Fig. 7.15: Characteristic of distance protection**

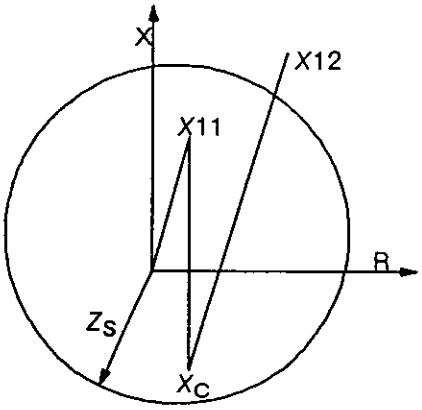



**Fig. 7.16: MHO-Characteristic, crosspolarized**

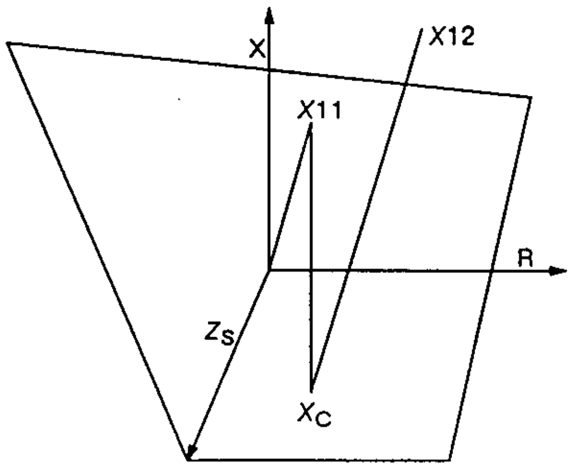



Fig. 7.17: Quadrilateral Characteristic, Crosspolarised

### 7.4.1.3 Negative relay impedance, negative fault current

If ($Xc$) > ($X11$ + $Xs1$) in figure 7.18 and a fault occurs behind the capacitor, the resultant impedance becomes negative and the fault current will have opposite direction compared with fault current in a power line without a capacitor. The negative direction of the fault current will persist until the airgap has flashed. Sometimes there will be no flashover at all, because the fault current is less than the setting value of the airgap. The negative fault current will cause a high voltage on the network. The situation will be the same even if a resistor-airgap is used. However, depending upon the setting of the resistor, the fault current will have a resistive component.

The problems described here are accentuated with a three phase or phase-to-phase fault, but the negative fault current can also exist for a single-phase fault. The condition for a negative current in case of an earth fault can be written as follows:

$$[3X_C] > [2 \cdot X_{L11} + X_{L10} + 2 \cdot X_{S11} + X_{S10}]$$

The good protection systems must be able to cope with both positive and negative direction of the fault current, if such conditions can occur.

A distance protection cannot operate for negative fault current. The directional element gives wrong direction. So, if a problem with negative fault current exists, a distance protection is not a suitable protection. Fortunately this seldom occurs. In normal network configurations the gaps will flash in this case.

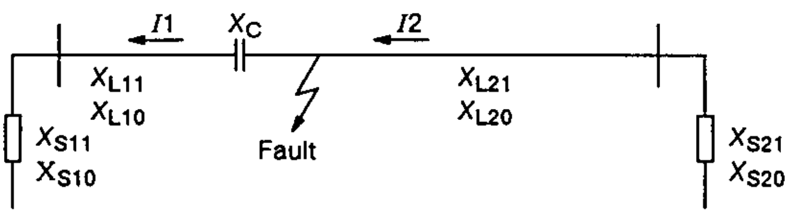



Fig. 7.18: Negative fault current

### 7.4.1.4 Double circuit series-compensated power lines

Two parallel power lines ending at the same busbar at both ends will cause some problems for distance protection because of the mutual impedance in the zero sequence system. The current reversal phenomena will also raise problems from the protection point of view, particularly when the power lines are short and when permissive overreach schemes are used.

See figure 7.19: The problem will be aggravated when the power lines are equipped with series capacitors. The capacitor will compensate the self impedance in the zero sequence network while the mutual impedance will be the same as on non-compensated power line. The effect of the mutual impedance will therefore be worse than for non-compensated double lines. If there exists negative impedance and negative fault current at the same time and a good phase selection is required for single pole autorelosure, the number of problems for a distance protection system will be tremendous.

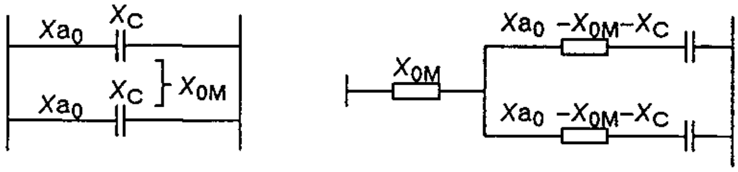



**Fig. 7.19: Series compensated parallel power lines (zero-sequence system)**


**Fig. 7.20: Current reversal phenomena**

If a permissive overreach system is used in accordance with figure 7.20 and a fault occurs in the far end in one of the power lines, both protections at A will send signals to B. The protection on the faulty line at B, which has detected the fault in the corrent direction, will initiate tripping. As soon as the circuit-breaker has opened the current in the healthy power line will reverse and if the signal is still received from the remote end, the healthy power line may falsely trip. (This was also discussed in section 4.2.2.) It is to be noted that the current in the reverse direction will increase very much in magnitude due to the mutual impedance and the series compensation.

To avoid the unwanted tripping, some manufacturers provide a feature in their distance protection which detects that the faultcurrent has changed in direction and will temporarily block the protection (transient blocking function, see 4.3.1.3).

Others will temporarily block the signals received at the healthy line as soon as the parallel faulty line protection initiates tripping.

The second mentioned method has an advantage in that not the whole protection is blocked for a while. The disadvantage is that a local communication is needed between two protections in the neighbouring bays of the same substation.

Distance protection used on series compensated lines must have a high overreach to cover the whole power line also when the capacitors are out of service. When the capacitors are in service, the overreach will increase tremendously and the whole system will be very sensitive for false telesignals. Current reversal problems will be accentuated because the ratio of mutual impedance against selfimpedance will be much higher than for a non-compensated line.

In principle a phase- segregated unit protection and particularly a longitudinal differential protection seem to be the best protection in the case when short power lines are compensated. It will cover the underreach, negative impedance and partly also negative fault current problems.

If a non-unit protection is to be used in a directional comparison mode, schemes based on negative sequence quantities offer the advantage that they are insensitive to mutual coupling. However, they can only be used for phase-to-earth and phase-to-phase faults. For three-phase faults another protection must be provided.

## 7.4.2 Directional comparsion protection

### 7.4.2.1 Directional comparison travelling wave protection

This kind of power line protection is a directional comparison protection. It can be very fast and make its measurement only when the fault occurs and a short time thereafter. Then the protection seals-in. It measures the changes of voltage $\Delta U$ and current $\Delta I$. These values can be calculated in a steady-state manner when a voltage source is assumed at the fault-location in accordance with the Thevevin's therorem. The settings of ΔU and ΔI give the reach of the protection, while comparison of the signs of $\Delta U$ and $\Delta I$ give the direction. The protection is set in an overreaching mode, as in all directional comparison schemes. If the signs are equal, the fault is in reverse direction. If the signs are different, the fault is in forward line direction. In principle this protection is better than distance protection and can cope with all the problems presented in the chapter on distance protection, like underreach, negative impedance and negative fault current. However, in parallel power lines it has the same problem as all overreach protections. Figure 7.21 below shows the protection principle for different fault locations.

The disadvantages of this protection is that the protection is only active for a short time after the occurrence of the fault and then seals-in (blocks) a certain time. This means it has some weaknesses concerning evolving faults.

This kind of protection should be designed in such a way that it will not operate when arresters flash. It should have different measuring elements for earthfaults and phase-to-phase faults and be at the same time a good phase selector.

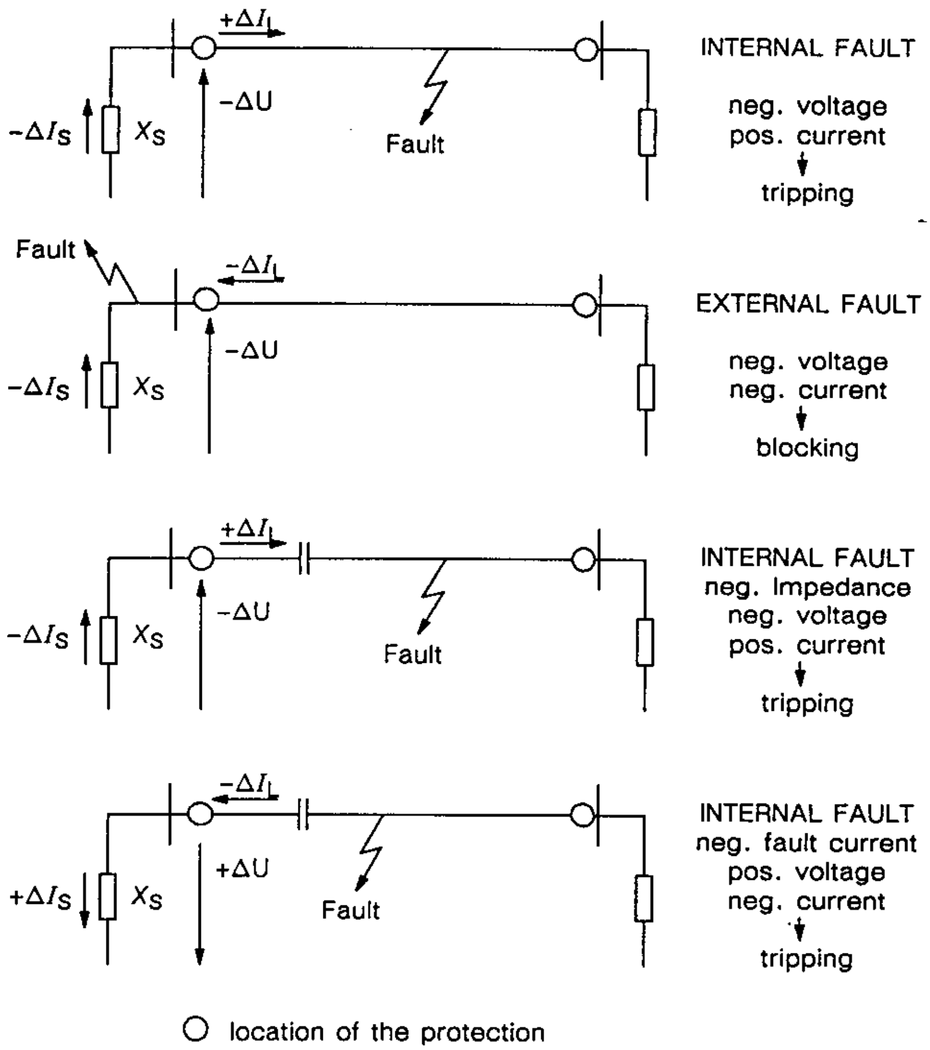



**Fig. 7.21: Principle of travelling wave protection**

### 7.4.2.2 Directional residual overcurrent protection

This protection operates only with zero sequence components, and thus it can only operate for earth faults. It also works correctly for series faults (interruption in one or two phases). The directional relay is fed with zero sequence voltage and current and one can say that the protection operates with the zero sequence quantities $\Delta U_0$ and $\Delta I_0$ similar to the travelling wave method demonstrated in figure 7.21.

The protection is set to an overreach mode and has the same advantages compared with distance protection as the travelling wave protection, except that it does not operate for non-earth faults. It has the disadvantages that the reach varies slightly with the source impedance. The protection will be more complicated if it is used in combination with singlepole reclosing, because an internal fault situation appears to the relay during the dead-time when one pole is open. This protection must therefore be blocked during the dead-time.

It operates with steady-state quantities and the protection is always active which is considered an advantage compared with the travelling wave protection. It works for series faults as well if an interruption is located inside the protection zone. The reach of the overreaching zone is limited by an overcurrent residual relay. Figure 7.23 shows how the protection operates for different fault locations on lines with or without compensation.

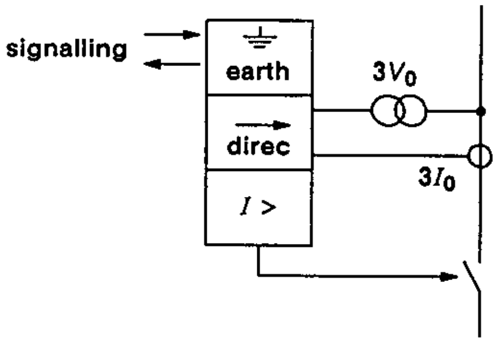



Fig. 7.22: Directional element of a residual current comparison protection

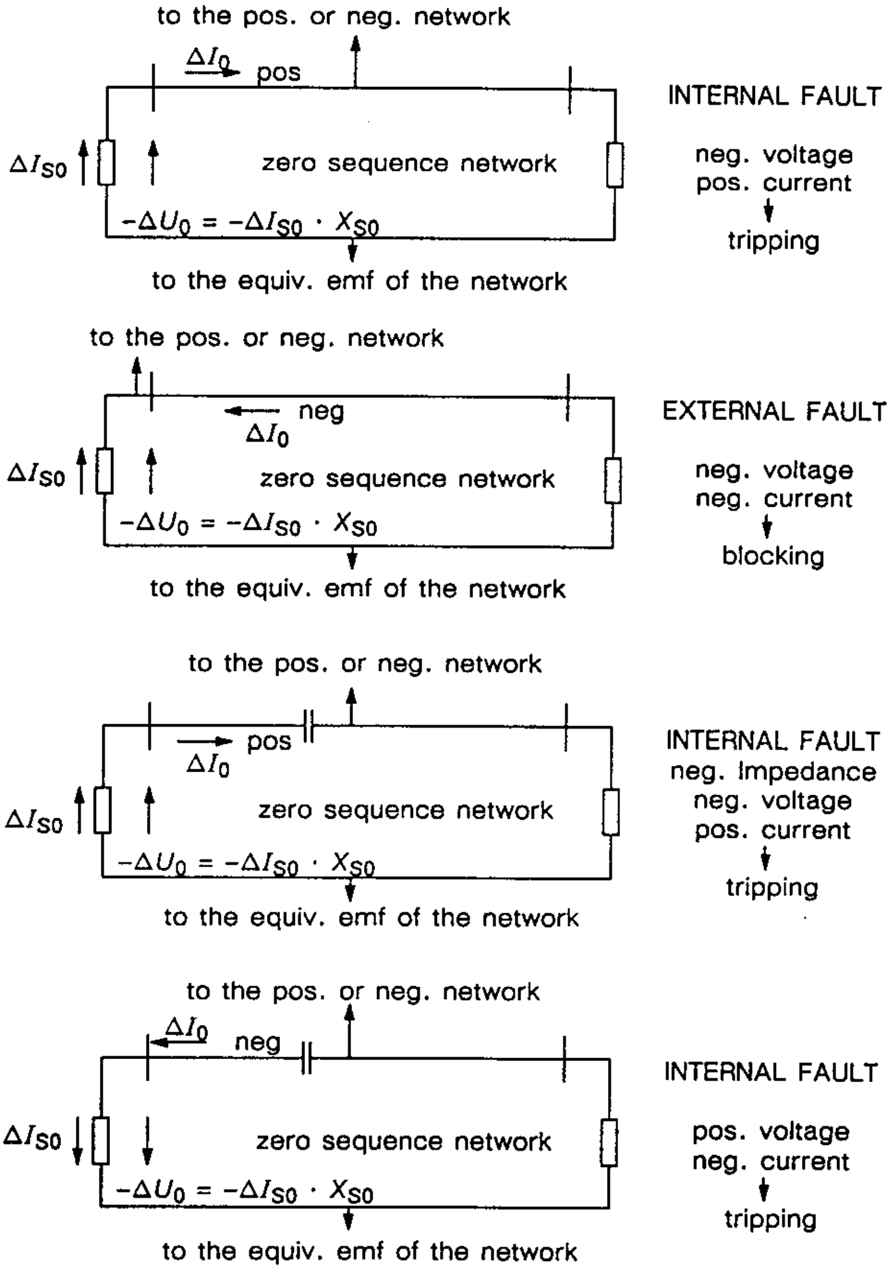



**Fig. 7.23: Principle of the directional residual-current protection**

### 7.4.2.3 Negative sequence overcurrent protection

Similar functions as in 7.4.2.2 can obtained by using negative sequence instead of zero sequence quantities. The use of negative sequence quantities has advantages in parallel power lines where the mutual coupling exists in the zero sequence network. This protection can be preferred for series-compensated parallel power lines described in section 7.4.1.4. The protection has the same disadvantage as the residual current protection concerning single pole autoreclosing.

## 7.5 Power line protection based on unit principles

### 7.5.1 Phase comparison protection

A phase comparison protection compares the phase position of the currents at each end as compared to the remote line end currents. For the through-fault condition the angle is small. In the event of an internal fault the angle is high. The protection operates when the angle difference is larger than the setting value.

$$\text{angle } I_1 - \text{angle } I_2 > \text{angle } \varnothing$$

The protection is often used on series compensated power lines. It has no underreach problem and no problem with negative impedance. It is not affected by mutual coupling. However, it will not operate in case of negative fault currents until the gaps have flashed.

With a resistor-airgap-protected capacitor it must be taken into consideration that in some internal fault cases the angle of the two fault-loops will deviate from the normal about 180 degrees because there is a resistor in one of them.

In a number of older installations the composite-type of PCP is still in service. It is, however, no longer considered as up-to-date practice. The perceived problem is that the mixed-current output of the symmetrical-component filter may not be sufficiently high for certain combinations of internal fault types and unsymmetrical flashing of the capacitor protective gaps.

Phase-segregated types are therefore recommended.

### 7.5.2 Longitudinal differential protection

This protection operates when differential current has reached a value sufficient to overcome the restraint developed in the peculiar design. The differential current is defined as the sum of the current at all ends of the protected section taking the magnitude and the angle into consideration.

$$I\text{d} = I_1 + I_2$$

During normal operation Id is nearly zero and for external faults as well. Normally the protection is stabilised with through current and the operating value depends upon the amount of stabilising current. It can be used for series compensated power lines because there will be no underreach problem and no negative impedance problem. At negative fault currents the angle will be roughly the same at both ends of the power line, but the magnitude of the current will in the normal case be different and the protection can operate. However stabilising current can be of such magnitude that the protection fails to trip.

Up to now, pilot wires have been used as communication media and consequently the protection could be used only for short power lines. Developments in optical fibre or radio link communication make it now possible to use this kind of protection over longer distances. If phase selection is of importance, it should be designed as a phase-segregated protection.

In principle this protection should be useful especially on shorter series compensated power line sections. The distance overreach problem in combination with current reversal could be managed in a better way.

However, the advantages of strict phase- and zone-selectivity of this unit protection can also be used on longer lines. Series-compensated lines of 190km length are protected in Japan by the Microwave type PCP.

## 7.6 Automatic reclosing (AR) and reinsertion

When the compensation degree and location of the capacitor are such that the airgaps flash only for faults located on the power line and not for external faults, the high-speed reclosing can be organised in the same way as on a non-compensated power line.

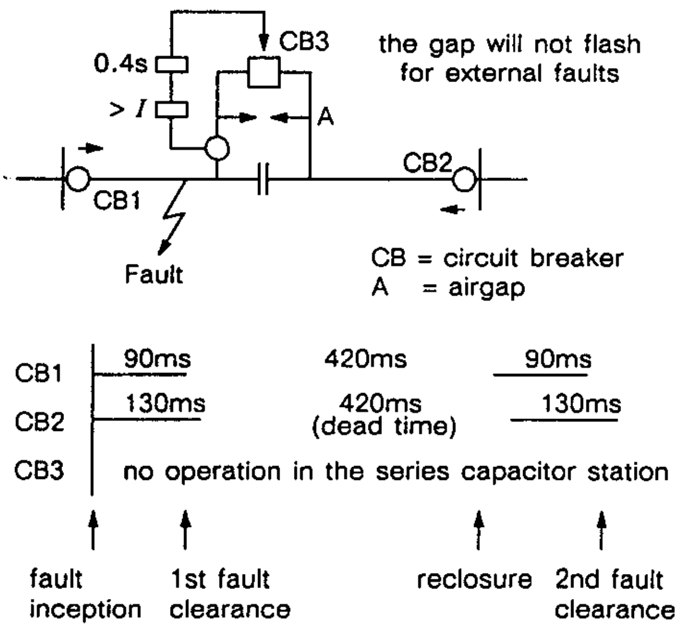
If a fault occurs in the neighbourhood of the capacitor, the airgap flashes but the circuit-breakers of the capacitor segments do not close because the overcurrent protection in series with airgap is delayed by approximatly 0.4 s in accordance with the figure 7.24. The fault clearance time at both ends of the power line is much shorter, so the current through the airgap is interrupted, and the overcurrent protection on the series-capacitor will reset. Also in resistor-airgap-protected capacitors the same scheme can be used because the airgap will normally not flash for external faults.

The circuit-breakers at the end of the power line reclose and, if the fault is transient, everything reverts to the same situation as before fault occurrence. If the fault is sustained, the procedure will be repeated and the circuit-breaker at the ends of the line will stay in an open position. It is to be noted that the airgap is cleared without any operation from the protection at the series capacitor station. The same philosophy is valid for three-pole AR as well as for single-pole AR.

If the capacitor location and the compensation degree provide a situation that the gaps also flash for external faults, the automatic control circuitry in the capacitor station must also be included in a high-speed-reclosing scheme. See figure 7.25. When such a fault is cleared by the protection outside the series compensated line, the load current in the airgap is sustained and the by-pass circuit-breaker has to close as soon as possible in order to protect the airgap.

The time setting for opening the circuit-breakers of the capacitor bank is about 0.2 s. It is important to let the by-pass circuit-breaker reopen, because the compensation has to be kept in operation when one or perhaps more power lines have been lost.

The same procedure will be repeated if the fault is sustained. With internal faults the by-pass circuit-breakers has to close and reopen during a normal high-speed reclosing operation. The automatic control circuitry in the series-capacitor station must harmonise with line AR-automatic control circuitry. A delayed reopening function also exists which normally takes place after 30 s. The described philosophy is valid both for single and three pole reclosing.




If the power line protections will trip later than 0.4 s, the capacitor will be shorted by the by-pass circuit-breaker initiated by the over-current protection. If the fault is sustained the circuit-breaker will be reopened once again after 30 s.

**Fig. 7.24: High-speed automatic reclosing, internal fault**

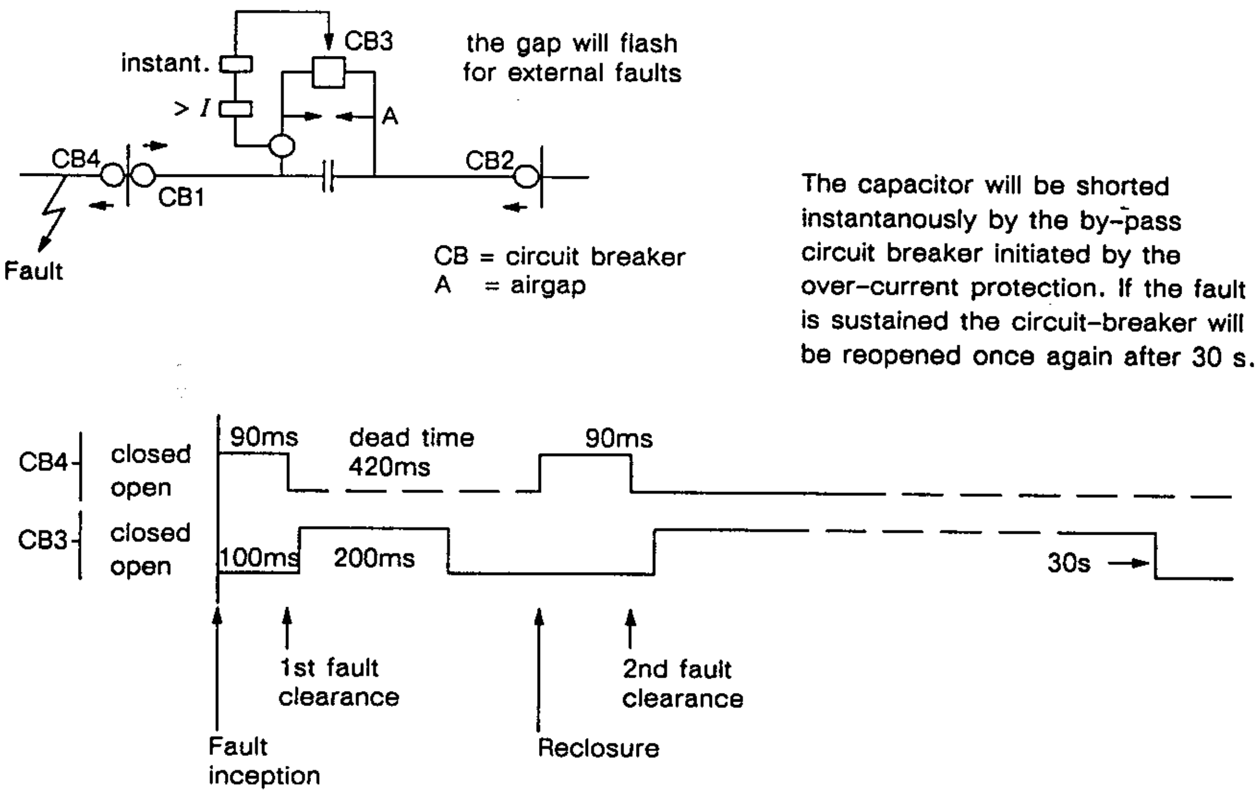



Fig. 7.25: **High speed automatic reclosing on an external fault**

## 7.7 Protection against high resistance faults and pole-discrepancy

None of the protections described above can be set with such sensitivity that it can operate for high-resistance faults and series faults. The residual current and the negative sequence current comparison described in section 7.4.2.2 and 7.4.2.3 can be set with high sensitivity but the overreach at low resistance fault would be too long and the protection would not be secure against false carrier signals. It is not recommended for detection of high resistance faults without modifications.

In the U.S., good results have been achieved by using the magnitude of positive sequence current as a restraining factor. Typical arrangements use as operating quantity

$$I_0 - K \cdot |I_1| \text{ or } I_2 - K \cdot |I_1|$$

It is claimed that high-resistance faults up to several hundred ohms can be detected with the usual CT ratios applied on EHV lines.

Alternatively or additionally a protection can be added which fulfills the requirement of clearing small zero-sequence currents. Normally a low-set residual current relay can be satisfactory. To obtain the best selectivity it should have an inverse time characteristic. All bays should be equipped with such relays having the same primary setting and the same characteristic. This means that the relay closest to the fault will have the highest current and consequently will trip before the others. This protection will trip if the capacitor e.g. stays with two poles (phases) in operation and one out of operation. This protection usually does not start any high-speed reclosing equipment.

## 7.8 Subsynchronous resonance SSR

A series compensated network has a natural electrical frequency in the subsynchronous range. This can cause resonance with the mechanical system of a turbine-generator shaft. The problem is mainly related to large turbogenerators, where mechanical frequencies of 10 to 40 Hz are common. Damage has occurred in service, but has been found to be a very rare event. Hydrogenerators are not affected since their mechanical frequencies are usually below 10 Hz.

Subsynchronous oscillations can be created by switching operations and by faults in a network. Countermeasures are available that either suppress the oscillations or bring the system out of resonance. As a last step, a threatened generator can be disconnected.

Subsynchronous resonance (blocking) filters and controllable static var devices have been used to counteract SSR but represent very expensive solutions. Small oscillations can be very effectivly suppressed by means of a suitable exciter control system (PSS).

By-passing of the series capacitor, or part of it, brings the system out of resonance, but can have certain disadvantages such as reduced system stability. An improvement can be obtained by means of a dual-gap protection, introducing a non-linear resistor in parallel with the capacitor. The effectiveness of such a method has been investigated for a 420 kV series-compensated power line connected to a large nuclear power generator. The result was very encouraging. A triggered gap may be need, however, to get the resistor sufficient fast operative.

Subsynchronous conditions can be detected by means of subsynchronous oscillation relays (7.18) and by a direct monitoring of the shaft speed and torque oscillations on the generator. A method using thin metallic pulse bands secured to the shaft has been developed and successfully tested on large generators. The pulse are picked up by eddy-current transducers and processed in electronic circuits to give speed and torsional deviations or derivatives of these. The accuracy is very high. In this way the shaft behavior can be monitored at different locations, which is also of benefit during stresses caused by other operating conditions such as network faults close to the generator, high speed power line reclosing etc. The resulting signals can be used to control the excitation, to trigger capacitor protections, and to disconnected the generator.

## 7.9 Placing of instrument transformers

If the series capacitors are located in the end of the power line there can be different ways to place voltage- and current transformers. The following figures show the most common alternatives.

In figure 7.26 the instrument transformers are placed between the busbar and the capacitor. Here we can have negative impedance and probably also negative current. A distance protection will have some difficulties if the requirement exists that the protection shall trip before the airgap flashes. The advantage is that the capacitor belongs to the power line and in the case of a shunt fault in the capacitor the power line protection will operate. A directional comparison or a unit protection should be preferred. If a distance protection is used faults on the adjacent line must also be taken into consideration.

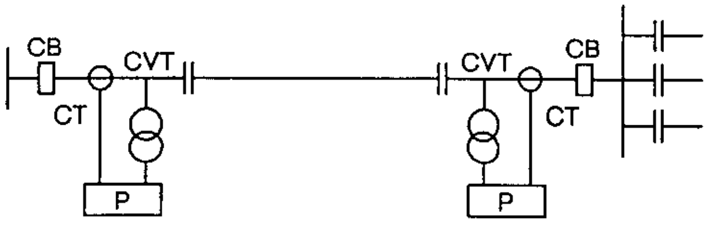



**Fig. 7.26: The instrument transformers are placed on the bus-side**

In figure 7.27 the voltage- and current transformer are placed on the power line-side of the capacitor. A distance protection will in this case not have any negative impedance. It will have a pure line to measure on. However, if one takes a fault on an adjacent line into consideration, the reach will also be limited to the first zone. It seems to be necessary to include the capacitor in the busbar protection or have a differential protection covering the capacitor itself. A distance protection can perhaps be equipped with features so it can also operate for faults between the busbar and the capacitor. If carrier is used for the protection, it has some advantages that signalling will not be disturbed by a flashing airgap in the same way as in figure 7.26 where the voltage transformer is placed on the bus-side.

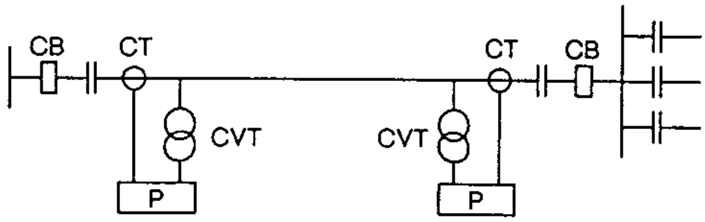



**Fig. 7.27: The instrument transformers are placed on the line- side**

In figure 7.28 the current transformer is placed on the bus-side and the voltage transformer on the line-side. This is common when there is a 2-breaker system in the substation. See figure 7.29 The advantage of this system compared to figure 7.27 seems to be that a possible unit protection will cover both the power line and the capacitor.

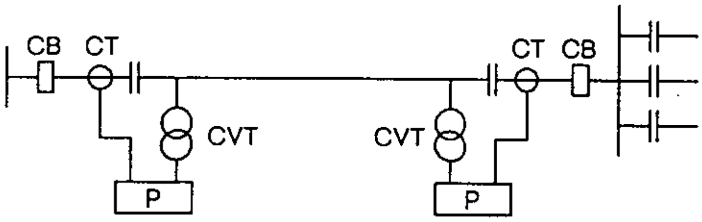



**Fig. 7.28: Current transformer on bus-side and voltage transformer on the line side**

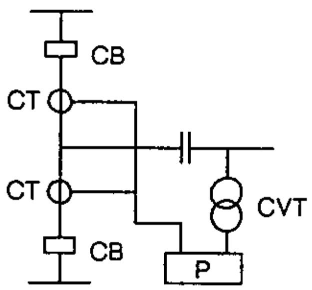



**Fig. 7.29: 2-circuit breaker system**

## 7.10 Applications

### 7.10.1 Sweden

In Sweden, eight 400 kV power lines are series compensated. The compensation degree varies between 70%-30%. All lines are mid-line compensated. Sometimes the compensation is divided into two banks in different locations on the power line. All banks except two are protected with conventional airgaps. Two are protected with resistor-airgap. All conventional ones will in the near future also be changed to the resistor-airgap version.

The basic requirement for the 400 kV Swedish network concerning protection of a series compensated power line can be summarised as follows:

Fault clearance time for close-up faults is 90 ms and for faults at the far end 130 ms. Two sets of protection are used, SUB1 and SUB2, and they are based on different principles. Circuit-breaker failure protection is installed and its fault clearance time is 250 ms after the occurrence of a close-up fault.

High speed three-pole autoreclosing with a dead time of 420 ms is practised. There is no synchrocheck except for power lines going to large thermal power stations.

SUB1 has distance protection of the electromechanical type. It is zone switched type and operates only for phase-to-phase faults and three-phase faults. It has a memory circuit. The first zone is set to underreach and the second and third zones are set to overreach even in series-compensated power lines. These relays are considered as a back-up protection. To achieve an overreaching instantantanous zone as recommended in section 7.4.1.1 for the permissive overreaching scheme, an extra measuring relay is installed. This is necessary because a switched scheme has only one measuring relay.

The distance protection mentioned above has no impedance measurement for earthfaults. Instead a directional residual current protection is used and this is connected in an overreach mode. Two zones are delayed and are considered as back-up protection in a similar way as with the distance protection.

A sensitive residual over-current relay with an inverse time characteristic is used to detect high resistance faults, CB pole discrepancy and phase-discrepancy between capacitors. The high-speed reclosing equipment and the circuit-breaker failure protection are placed in the SUB1.

SUB2 consists of a static switched type distance protection also containing earth fault measuring units. It is equipped with a memory circuit. This protection operates only in the underreach mode.

A travelling wave protection is placed on the same panel. It has both an underreaching and an overreaching mode.

Protection in SUB2 initiates high speed-reclosing and circuit-breaker failure in SUB1. Mostly, a common power line-carrier equipment with different channels for SUB1 and SUB2 is used.

## 7.10.2 Norway

**Basic requirements**

The protection of the 420 and 300 kV series compensated power lines shall

- clear the faults within 100ms
- enable single- and three-pole autoreclosure

**Series capacitor, location and protection**

The series capacitor locations are selected to ensure the best voltage profile in the power system. For the protection, this results in negative relay impedances in addition to several transient problems.
The capacitors are protected by ZnO-resistors, airgaps, and by-pass circuit-breakers. For internal line faults, the airgaps are allowed to flash immediately.For external faults, the Zn O -resistors in parallel with the capacitors are dimensioned to carry the maximum short circuit current for 120ms.When the energy capacity of the Zn O-resistors is expired, the air gap is triggered and the by-pass circuit-breaker is closed.

**Line protection**

The present standard on series compensated lines, and also on the adjacent lines, comprises two independent sets of line protection: Main 1 and Main 2.

Main 1 protection

One full scheme distance relay with the following characteristics/settings:

- Impedance starting elements, with quadrilateral characteristic
- Separate measurement of direction and distance
- Low set residual current detector ($3Io > 600A$) releases the phase to earth measuring units
- High set residual current detector ($3Io > 1500A$) blocks the phase-phase measuring units
- Directional decision is based on healthy phase polarization and a digital voltage memory (rectangular wave oscillator sychronized to the pre-fault voltage).
- Directional comparison scheme
- Current reversal blocking feature provided

A sensitive residual current relay ($3Io = 75A$) with inverse time characteristic is included to cover high resistance earth-faults.

Main 2 protection

Travelling wave relay with the following characteristics/settings:

- Three directional wave detecting modes:
  - Independent mode, operating on close-in high level faults without directional comparison
  - Dependent mode with directional comparison. Typical setting of the directional wave detectors: di > 1500A, du > 40kV
  - Neutral current controlled mode, operates similar to the dependent mode, but is set more sensitive and is controlled by the residual current ($3Io > 500A$)
- Measurement per phase
- One microwave channel
- Built-in back-up three-phase underimpedance relay (one zone), setting comparable to the distance relay zone 3 reach, delayed 0.9s.

Communication

The series compensated and their adjacent lines, have two separate communication channels each: one power line carrier link for the distance relay and one microwave link for the directional wave relay. Two separate channels are necessary because:

- the directional wave relay operates with "weak end infeed logic".
- the distance relays cannot operate with this feature in series compensated networks.

Busbar protection

There are no special requirements to the busbar protection itself. But, due to the series capacitors, remotely located distance relays may overreach and trip in the second zone if the fault is not cleared instantaneously in case of faults between the current transformer and the circuit breaker. Therefore the busbar protection initiates a permissive trip signal to enable the distance relays to trip the remote end breakers within 100ms.

Unsymmetrical faults, evolving faults and single phase operation of the capacitor protection, combined with 1Ø + 3Ø tripping, requires strict single-phase operation of the breaker failure protection.

Reclosing practice

For single pase tripping, high speed reclosing with a dead time of 900ms is applied. In case of three phase tripping, one end is high speed reclosed with a dead time of 400ms, and the other end is thereafter reclosed through synchrocheck.

### 7.10.3 Western North America

Series compensation is widely used on the EHV transmission lines of Western North America. Since a number of different power companies or authorities are involved, practices vary. However, certain generalizations can be made.

Both line-end and mid-line series capacitors have been used on various lines. Line-end installations have typically been designed for 35% compensation at each end, but 70% compensation at a single end has also been used. Older capacitors, installed in the 1960s and 70s use airgap protection; newer installations have the resistor-airgap type. Line relays for series compensated lines typically use two static protections, of either the same or different principles, depending upon the philosophy of the operating company. Phase comparison, travelling-wave directional comparison, and permissive overreach, with either distance relays or directional-overcurrent relays, have each been used.

For lines with line-end capacitors, a preference has been developed for installing the VTs for permissive overreaching schemes at the line-side related to the series capacitors rather than at the bus side. The advantages which are claimed for this approach are (a) a longer reach can be set on the zone 1 relay, where used, (b) the negative reactance problem is eliminated for internal faults (cross and memory polarizing is relied upon for external faults), (c) where the CVTs are used also for coupling of HF carrier signals, installation on the line side eliminates the gap-flashing noise from the carrier channel.

Because of the low source impedance at many stations (high short-cicuit power), negative fault current is a possibility. Most of the relay systems in use rely on protective gap flashover to prevent negative current. Many also have some means of coping with negative current for high resistance earth faults. These limitations have proven to be satisfactory in service.

### 7.10.4 South Africa

Eskom uses single and three pole tripping on approximately 80% of their series compensated lines. On the remainder, three pole only tripping is employed. Fault clearance times for close up faults are 60–70ms, and for remote end faults are 80–90ms. Eskom has mid-point (50% compensated) and single end-point (70% compensated) series compensated lines.

Eskom's series compensated lines are equipped at either end with one of two protection schemes, the one scheme being an earlier generation of protection relaying than the other. Both schemes have duplicated main primary protection relays.

On the older schemes, these primary protection relays, which are of the high speed electronic type, consist of a positive sequence distance relay and a negative sequence directional and overcurrent relay. Three phase faults are covered by the positive sequence relay and all unbalanced faults by the negative sequence relay. These schemes are used in both three pole only and single and three pole tripping applications. When applied as a single and three pole tripping scheme, a phase selector relay is incorporated to ensure correct phase selection for single pole tripping. On the more recent schemes, the primary protection relays, which are also of the high speed electronic type, are "full" distance relays comprising six directional underreaching (zone 1) measuring elemants and six directional overreaching (zone 2) measuring elements. These latter schemes are always applied as single and three pole tripping schemes.

The zone 1 elements are used to initiate direct tripping on series compensated lines as they are applied as hybrid overcurrent/distance functions. This is achieved by implementing a level detector in the operate signal set according to the capacitor bank gap flashover voltage level. When applied in this way, the zone 1 elements suffer a certain amount of pullback in reach and can be set to 100% of the line impedance. They will not operate for faults beyond the remote terminal of the line, but will operate for heavy faults close to the relay location. The zone 2 elements are applied as solely distance functions and are set to overreach the remote terminal of the line. All schemes have a memory circuit in their voltage polarising signals.

Blocking elements are also incorporated within the primary protection relays. This enables the protection schemes to be operated in the Hybrid Directional Comparison Tripping mode.

IDMT earth fault protection is incorporated to cater for high resistance earth faults. This protection is also duplicated on the more recent schemes, but not the older schemes.

A duplicated single pole breaker failure protection is installed on the more recent of the protection schemes on the series compensated lines (approximately 50%). The time delay between initiation of the breaker fail relay and a bus trip output is 120ms for a three pole tripping condition and 240ms for a single pole tripping condition. For the latter, a three pole retrip command is issued to the breaker after 120ms. On the older protection schemes, a single breaker failure protection is installed with a time delay of 120ms.

The schemes may be selected via a switch on the panel for fast or slow three pole reclosing. The dead time for fast reclosing is identical at both ends of the line and is set to 500ms. The dead time for slow three pole reclosing is set to 3s at the end selected for dead line charging and 4s at the end selected for synchronising.

## 7.11 Recent Practices and Trends

The attached charts summarize the replies to a CIGRE-questionnaire issued in 1989.

Replies to a CIGRE-questionaire circulated in 1989:

CIGRE SC34-WG04, Protection of Complex Transmission Network Configurations.

Reply to Questionnaire

Chapter E, Protection systems of series-compensated power lines.

# E.1 The use of series compensators, location and size.

| | E.1 Do you use series capacitors in your power system ? | E.1.1 To what extent do you use series compensation ? | | | E.1.2 $X_C/[X11+X12]$ is normally / not higher than ? | | | E.1.3 Where are the current- and voltage-transformers normally located in case of series capacitors at the line terminals ? | |
|---|---|---|---|---|---|---|---|---|---|
| | | a. With series capacitors at one line end only | b. With series capacitors not at the ends of the line | c. With series capacitors at both line ends | a. With series capacitors at one line end only | b. With series capacitors not at the ends of the line | c. With series capacitors at both line ends | CT | VT |
| Japan | Yes | 275kV: 2 | | | 275kV: 50% | | | Line side<br>Bus side | Line side |
| Argentina | Yes | 500kV: 4 | | 500kV: 2 | 500kV: 40% | | 500kV: 60% | Line side | Line side |
| Sweden | Yes | | 400kV: 8 | | | 400kV: 70% | | | |
| Norway | Yes | 300kV: 1 | 300kV: 5 | | 300kV: 40% | 300kV: 60% | | Bus side | Bus side |
| USA | Yes | 525kV: 4 | 525kV: 2 | 525kV: 4 | 525kV: 50% | 525kV: 80% | 525kV: 80% | Bus side | Line side |
| USSR | Yes | 500kV: 1 *) | | | 500kV: 40% | | | Bus side | Line side |
| ZA | Yes | 400kV: 7 | 400kV: 10 | | 400kV: 70% | 400kV: 40% | 400kV: 35% | Bus side | Line side |

*) Series-capacitors are introduced into buses of a substation at the centre of a double-circuit transmission line

## E.2 Series capacitors and their protection

| | E.2.1.1 Do you use zinc oxide arrestors ? | E.2.1.3 If yes, what is the impact on line protection ? | E.2.2 Will your air-gaps normally flash for faults outside the series-compensated line ? | E.2.3 How long can the airgap stand flashing without damage to the airgap ? | E.2.4 What is the setting of the airgap in relation to the rated voltage of the capacitor ? | E.2.5 Do you have protection so the circuit-breaker will automatically short-circuit the airgap ? |
|---|---|---|---|---|---|---|
| Japan | No | | No | $t_{max}$ = 1000 ms | $U_{Gap} = 2.4 \times U_{CN}$ | Yes |
| Argentina | No | | Yes | $t_{max}$ = 240 ms | $U_{Gap} = 2.2 \times U_{CN}$ | Yes |
| Sweden | Yes (in 2 cases) | | Yes | $t_{max}$ = 400 ms | $U_{Gap} = 3.0 \times U_{CN}$ | Yes |
| Norway | Yes | - increasing resistive apparent impedance<br>- deformation of the line-wave occurs<br>- incorrect distance-to-fault is measured | No | $t_{max}$ = 200 ms | $U_{Gap} = 2.0 \times U_{CN}$ | Yes |
| USA | Yes | - increasing resistive apparent impedance<br>- deformation of the line-wave occurs<br>- incorrect distance-to-fault is measured | Yes | $t_{max}$ = 2000 ms | $U_{Gap}$ = -- x $U_{CN}$ | Yes |
| USSR | Yes | | Yes | | $U_{Gap} = 3.7 \times U_{CN}$ | Yes |
| ZA | No | | No | $t_{max}$ = 600 ms | $U_{Gap} = 2.6 \times U_{CN}$ | Yes |

## E.2 Series capacitors and their protection

| | E.2.6 Do you use overcurrent protection in series with the air gap which will initiate closing of the circuit-breaker ? | E.2.7 If yes, what is the set delay of the overcurrent protection ? | E.2.8 Will the circuit-breaker re-open automatically after such an operation ? | E.2.9 If yes, what is the reinsertion delay ? a. Fixed time after circuit-breaker closing | E.2.9 b. After detected fault clearance | E.2.10 Please describe your reinsertion system for the series-capacitor. |
|---|---|---|---|---|---|---|
| Japan | Yes | Instantaneous | Yes | | t = 100 ms | |
| Argentina | Yes | t = 240 ms | Yes | t = 250 ms | | |
| Sweden | Yes | Instantaneous or t = 400 ms | Yes | t = 200 ms | | |
| Norway | Yes | Instantaneous | Yes | t = 200 ms | | |
| USA | Yes | t = 250 ms | No | | | |
| USSR | No | | No | | | Manual |
| ZA | Yes | Instantaneous | Yes | t = 250 ms | | 3 steps (automatic) |

## E.2 Series capacitors and their protection

| | E.2.11 What is the range of the ratio $\|X_C\|/\|X11+X12\|$ on your power lines ? | | | | E.2.12 What is the range of the ratio $\|X_C\|/\|X11\|$ on your power lines ? | | | | E.2.13 What is the range of the ratio $\|X_C\|/\|X11+X_{S1}\|$ on your power lines ? | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Positive sequence system | | Zero sequence system | | Positive sequence system | | Zero sequence system | | Positive sequence system | | Zero sequence system | |
| | Max | Min | Max | Min | Max | Min | Max | Min | Max | Min | Max | Min |
| Japan | 0.50 | 0.50 | 0.12 | 0.12 | Infin. | Infin. | Infin. | Infin. | 0.98 | 0.00 | 0.95 | 0.00 |
| Argentina | | | | | | | | | | | | |
| Sweden | 0.76 | 0.37 | 0.17 | 0.10 | 360.00 | 0.50 | 12.00 | 0.13 | 1.70 | 0.30 | 0.37 | 0.11 |
| Norway | 0.60 | 0.40 | 0.26 | 0.15 | Infin. | 0.40 | Infin. | 0.17 | 0.61 | 0.26 | 0.60 | 0.23 |
| USA | | | | | | | | | | | | |
| USSR | 0.4 | 0.4 | 0.13 | 0.13 | 0.8 | 0.8 | 0.27 | 0.27 | | | | |
| ZA | 0.73 | 0.63 | 0.23 | 0.18 | 4.86 | 0.60 | 1.39 | 0.17 | 1.62 | 0.55 | 0.46 | 0.15 |

## E.2 Series capacitors and their protection

| | E.2.14 If $|X_C|/|X11+X_{S1}|$ can be possible in your power system ? | | |
|---|---|---|---|
| | Will the gaps always flash to avoid capacitive short circuit currents? | Do you require that the protection must operate selectively with or without flashover of the airgaps in this case? | |
| Japan | Yes | No | |
| Argentina | | | |
| Sweden | No | Yes | |
| Norway | | | |
| USA | Yes | Yes | |
| USSR | No | No | |
| ZA | N/A | N/A | |

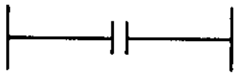
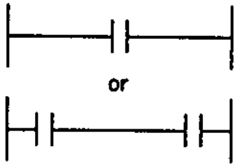
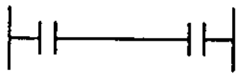
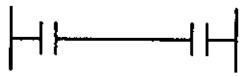
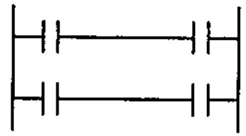
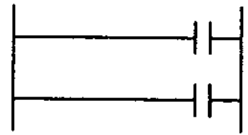
CIGRE SC34-WG04, Protection of Complex Transmission Network Configurations.

Reply to Questionnaire

Chapter E, Protection systems of series-compensated power lines.

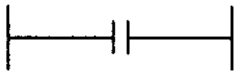
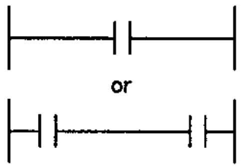
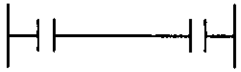
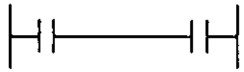
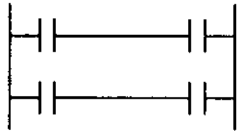
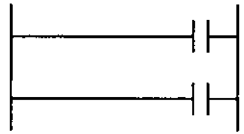
# E.3 Protection of series-compensated lines.

## E.3.1 Primary protection, table 10.

| | Case 1: | Case 2: | Case 3: | Case 4: | Case 5: | Case 6: |
|---|---|---|---|---|---|---|
| |  $X_C < 0.5 \cdot X_L$ |  $X_C < X_S$ at both line ends |  $X_C > X_S$ possible but gaps flash in this case |  $X_C > X_S$ possible |  |  |
| Japan | | | | | | Ph MWDP (FM)<br>E MWDP (FM) |
| Argentina | | | | | | |
| Sweden | PODP<br>DEPZ, NDEP | | | | | |
| Norway | Ph TWMP<br>E TWMP, NDEP | | | | | |
| USA | see section 7.10.3 | ← | | | | |
| USSR | PODP, DEPN | | | | | |
| ZA | Description, see section 7.10.4 | ← | | | | ← |

# E.3 Protection of series-compensated lines.

E.3.2 Secondary protection, table 11.

| | Case 1:  $X_C < 0.5 \cdot X_L$ | Case 2:  $X_C < X_S$ at both line ends | Case 3:  $X_C > X_S$ possible but gaps flash in this case | Case 4:  $X_C > X_S$ possible | Case 5:  | Case 6:  |
|---|---|---|---|---|---|---|
| Japan | | | | | | Ph DPO<br>E DPO, MWDP(FM) |
| Argentina | | | | | | |
| Sweden | PODP, TWCP | | | | | |
| Norway | Ph PODP<br>E PODP | | | | | |
| USA | SPCP, TWMP see section 7.10.3 | SPCP, TWMP see section 7.10.3 | | | | |
| USSR | | | | | | |
| ZA | PODP, DEPN see section 7.10.4 | PODP, DEPN see section 7.10.4 | | | | PODP, DEPN see section 7.10.4 |

## E.3 Protection of series-compensated lines.

| | E.3.2.1<br>If distance protection is used, do you set the first zone in the order of 0.85 * $(X_{11} + X_{12})$ ? If not, what is your setting ? | E.3.2.2<br>If permissive overreach is used, do you change settings when the capacitor is shorted or is taken out of service ? | E.3.2.3<br>If permissive overreach is used, do you set the overreach zone in the order of 1.3 * $(X_{11} + X_{12} - X_C)$ ? If not, what setting is used ? | E.3.3<br>If $\lvert X_C\rvert > \lvert X_{11}\rvert$ the resultant reactance will be negative. This situation is normally called negative relay impedance.<br>Do you use special phase-locked voltage memories for directional decision of the distance protection to take care of this problem ?<br>If no, what precautions have you provided ? |
|---|---|---|---|---|
| Japan | Yes | | | Yes |
| Argentina | No (= $X_{11}$) | | No | Yes |
| Sweden | No 0.8 $(X_{11} + X_{12} - X_C)$ | No | No 1.3 $(X_{11} + X_{12})$ | No |
| Norway | No 0.8 $(X_{11} + X_{12} - X_C)$ | | No 1.3 $(X_{11} + X_{12})$ | Yes |
| USA | | No | Yes | Yes |
| USSR | | No | No | No<br>Negative sequence power relay |
| ZA | | No | No | No |

# E.3 Protection of series-compensated lines.

| | E.3.4 If $\|X_C\| > \|X_{11} + X_S\|$ the fault-current will have an opposite direction. This situation is normally called negative relay current. If you do not rely on gap flashover, what precautions do you take against this phenomenon ? | | E.3.5 Do you make any allowance in your settings for a slight delay so the protection system not will operate before the airgap has flashed ? | E.3.6 If unit protection is used, will you make any extra arrangements because of the negative relay reactance ? What kind ? | E.3.7 If unit protection is used, will you make any extra arrangements because of the negative relay current ? Please describe. |
|---|---|---|---|---|---|
| | Rely on gap flash-over | Other precautions | | | |
| Japan | Yes | | Yes, 120ms | No | No |
| Argentina | | | No | No | No |
| Sweden | No | by using TWP and NDEP | Yes, 100ms | No | No |
| Norway | | | No | No | |
| USA | Yes | | | | |
| USSR | Blocking by negative sequence power relays | Yes | No | Yes Blocking by negative sequence power relays | |
| ZA | | Yes | No | | No |

# E.3 Protection of series-compensated lines.

E.3.8 With series compensated short double circuit power lines, the mutual impedance plays an important role. The capacitor will reduce the self impedance while the mutual impedance will be the same as it is without series capacitors. This means that the effect of the mutual impedance will be much higher than on power lines without series capacitors.

| | E.3.8.1 Have you experienced protection problems on this basis ? | E.3.8.2 Do you think a unit protection is the best protection for these kind of power lines ? | E.3.8.3 Will you have flashover only of the faulty line capacitor (or will flashover also occur on the healthy power lines ? | E.3.8.4 Does unsymmetrical flashover of the gaps occur in your power system ? | E.3.8.5 If the answer to 3.8.4 is yes, what problems have been experienced and what countermeasures have been taken ? |
|---|---|---|---|---|---|
| Japan | No | Yes | No | Yes | No problems |
| Argentina | No | No | Yes | Yes | No problems |
| Sweden | Yes | Yes | No | Yes | |
| Norway | | No | No | Yes | No problems |
| USA | | | | | |
| USSR | No | | | | |
| ZA | N/A | | | | |

## 7.12 Transients on series compensated lines

A network with series capacitors is essentially equivalent to a series oscillating R–L–C circuit which, in case of faults, is excited to oscillate.

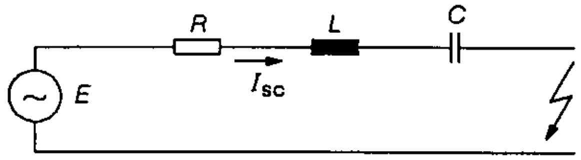



**Fig. 7.30: Short-circuit loop of a series compensated line**

The differential equation of this circuit is:

$$E_m \cdot \sin(\omega t + \lambda) = L \frac{d^2 I_{sc}}{dt^2} + R \frac{d\, I_{sc}}{dt} + \frac{1}{C} I_{sc} dt$$

By resolving this equation, the following expression is obtained for the short-circuit current:

$$I_{sc} = \frac{E_m}{Z} \cdot \sin(\omega t + \lambda - \Theta) + e^{-\alpha t} (K_1 \cos\beta t + K_2 \sin\beta t)$$

With the constants:

$$K_1 = I_0 - \frac{E_m}{Z} \cdot \sin(\lambda - \Theta)$$

$$K_2 = \frac{1}{\beta L} [E_m \cdot \sin\lambda - U_{C0} - \frac{R}{2} I_0 - E_m \cdot \frac{X_L}{Z} \cos(\lambda - \Theta) - E_m \cdot \frac{R}{2Z} \sin(\lambda - \Theta)]$$

$$Z = \sqrt{R^2 + (\omega L - \frac{1}{\omega C})^2}$$

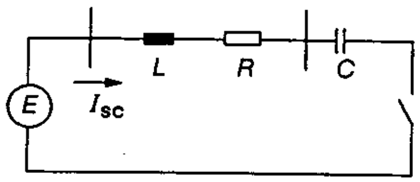
$$\Theta = \text{arctg} \frac{X_L - X_C}{R}, \quad \alpha = \frac{R}{2L}, \quad \beta = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

| | | |
|---|---|---|
| $E_m$ | | Amplitude of the feeding voltage |
| $X_L$ | $= \omega L$ | Reactance of the short-circuit loop |
| $X_C$ | $= 1/\omega C$ | Capacitive reactance of the series capacitor |
| R | | Ohmic resistance of the short-circuit-loop |
| $U_{C0}$ | | Potential difference across the capacitor at fault-inception |
| $I_0$ | | Load current at fault-inception |
| $\lambda$ | | Instant of fault-inception |

The short-circuit current is therefore composed of a steady-state part and a damped sinusoidal transient oscillation. This latter has the frequency $\beta$ and dies out with the time-constant $\alpha$. It is an equivalent to the d.c. component which appears in a normal L–R short-circuit-loop.

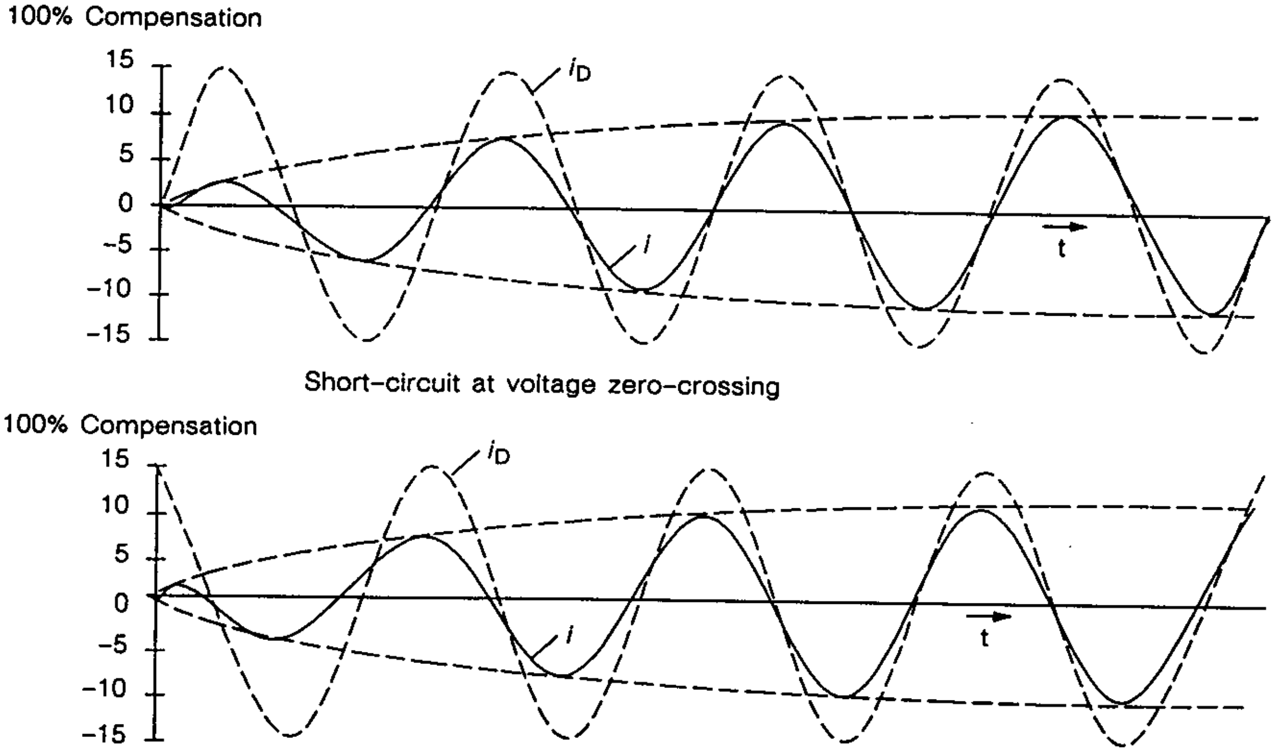
In figure 7.31 the short-circuit current $I_{s.c.}$ is shown for different degrees of compensation ($k = X_C/X_L$) and different instants of point-on-wave fault-inception.

A particularly characteristic feature is the delayed beginning of the oscillations and the overshooting beyond the stationary value after a few cycles.




f = 60 Hz
E = 188 kV
ωL = 82 Ω
R = 12.9 Ω

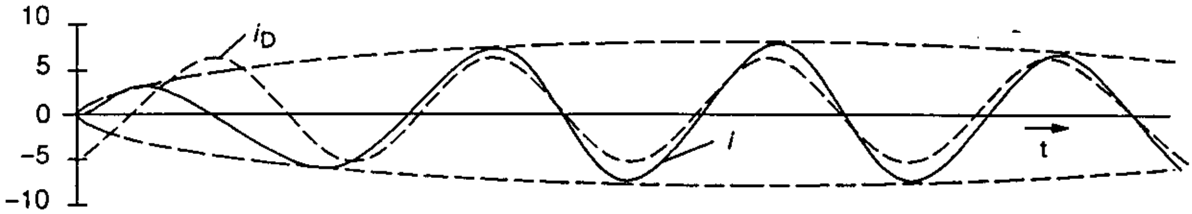
Fig. 7.31: Current transients in an L-C-R circuit at fault-inception




Short-circuit at voltage maximum
$i$ = total current
$i_D$ = steady-state current

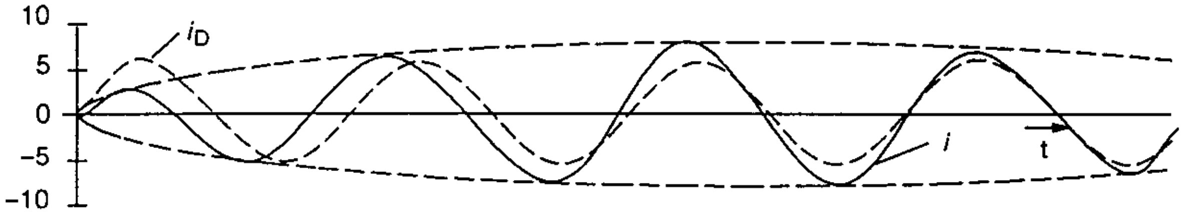
Fig. 7.32a: Short circuit current of a series compensated line, 100% compensation

57% Compensation




Short-circuit at voltage zero-crossing

57% Compensation




Short-circuit at voltage-maximum

$$i = \frac{E}{Z} \cdot \sin(\omega t + \lambda - \Theta) + \frac{Ed}{BL} e^{-\alpha t} \cdot \sin \Theta t - \frac{E}{Z} \sin(s - \Theta)\, e^{-\alpha t} \cdot \cos \Theta t$$

$$E_d = E \cdot \sin \lambda - \frac{Q_0}{C} - E \frac{\omega_L}{Z} \cos(\lambda - \Theta) - E \cdot \frac{R}{2Z} \sin(\lambda - \Theta)$$

$Q_0 = 0$ at $t=0$

$\omega = 377 \frac{1}{sec}$ (60Hz) $\qquad \alpha = \frac{R}{2L}$ ; $B = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$

$\Theta$ = line angle $\qquad \lambda$ = angle of E at $t=0$

**Fig. 7.32b: Short circuit current of a series compensated line, 57% compensation**

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