

. 10 . *Unit Protection of Feeders*

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• 10 • *Unit Protection of Feeders*

10.1 INTRODUCTION

The graded overcurrent systems described in Chapter 9, though attractively simple in principle, do not meet all the protection requirements of a power system. Application difficulties are encountered for two reasons: firstly, satisfactory grading cannot always be arranged for a complex network, and secondly, the settings may lead to maximum tripping times at points in the system that are too long to prevent excessive disturbances occurring.

These problems led to the concept of 'Unit Protection', whereby sections of the power system are protected individually as a complete unit without reference to other sections. One form of 'Unit Protection' is also known as 'Differential Protection', as the principle is to sense the difference in currents between the incoming and outgoing terminals of the unit being protected. Other forms can be based on directional comparison, or distance teleprotection schemes, which are covered in Chapter 12, or phase comparison protection, which is discussed later in this chapter. The configuration of the power system may lend itself to unit protection; for instance, a simple earth fault relay applied at the source end of a transformer-feeder can be regarded as unit protection provided that the transformer winding associated with the feeder is not earthed. In this case the protection coverage is restricted to the feeder and transformer winding because the transformer cannot transmit zero sequence current to an out-of-zone fault.

In most cases, however, a unit protection system involves the measurement of fault currents (and possibly voltages) at each end of the zone, and the transmission of information between the equipment at zone boundaries. It should be noted that a stand-alone distance relay, although nominally responding only to faults within their setting zone, does not satisfy the conditions for a unit system because the zone is not clearly defined; it is defined only within the accuracy limits of the measurement. Also, to cater for some conditions, the setting of a stand-alone distance relay may also extend outside of the protected zone to cater for some conditions.

Merz and Price [10.1] first established the principle of current differential unit systems; their fundamental differential systems have formed the basis of many

highly developed protection arrangements for feeders and numerous other items of plant. In one arrangement, an auxiliary 'pilot' circuit interconnects similar current transformers at each end of the protected zone, as shown in Figure 10.1. Current transmitted through the zone causes secondary current to circulate round the pilot circuit without producing any current in the relay. For a fault within the protected zone the CT secondary currents will not balance, compared with the through-fault condition, and the difference between the currents will flow in the relay.

An alternative arrangement is shown in Figure 10.2, in which the CT secondary windings are opposed for through-fault conditions so that no current flows in the series connected relays. The former system is known as a 'Circulating Current' system, while the latter is known as a 'Balanced Voltage' system.

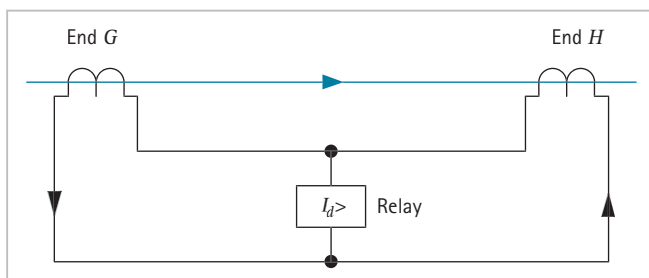


Figure 10.1: Circulating current system

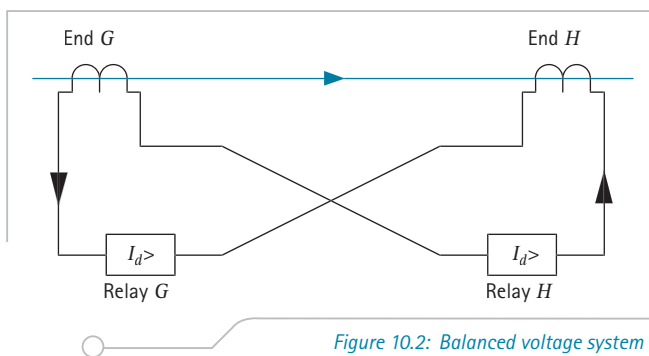


Figure 10.2: Balanced voltage system

Most systems of unit protection function through the determination of the relative direction of the fault current. This direction can only be expressed on a comparative basis, and such a comparative measurement is the common factor of many systems, including directional comparison protection and distance teleprotection schemes with directional impedance measurement.

A major factor in consideration of unit protection is the method of communication between the relays. This is covered in detail in Chapter 8 in respect of the latest fibre-optic based digital techniques. For older 'pilot wire' systems, only brief mention is made. For more detailed descriptions of 'pilot wire' techniques, see reference [10.2] in Section 10.13.

10.2 CONVENTION OF DIRECTION

It is useful to establish a convention of direction of current flow; for this purpose, the direction measured from a busbar outwards along a feeder is taken as positive. Hence the notation of current flow shown in Figure 10.3; the section GH carries a through current which is counted positive at G but negative at H , while the infeeds to the faulted section HJ are both positive.

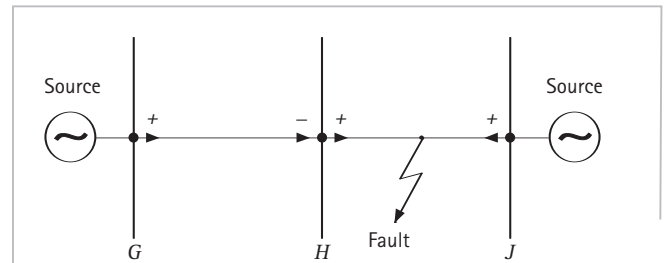


Figure 10.3: Convention of current direction

Neglect of this rule has often led to anomalous arrangements of equipment or difficulty in describing the action of a complex system. When applied, the rule will normally lead to the use of identical equipments at the zone boundaries, and is equally suitable for extension to multi-ended systems. It also conforms to the standard methods of network analysis.

10.3 CONDITIONS FOR DIRECTION COMPARISON

The circulating current and balanced voltage systems of Figures 10.1 and 10.2 perform full vectorial comparison of the zone boundary currents. Such systems can be treated as analogues of the protected zone of the power system, in which CT secondary quantities represent primary currents and the relay operating current corresponds to an in-zone fault current.

These systems are simple in concept; they are nevertheless applicable to zones having any number of boundary connections and for any pattern of terminal currents.

To define a current requires that both magnitude and phase be stated. Comparison in terms of both of these quantities is performed in the Merz-Price systems, but it is not always easy to transmit all this information over some pilot channels. Chapter 8 provides a detailed description of modern methods that may be used.

10.4 CIRCULATING CURRENT SYSTEM

The principle of this system is shown in outline in Figure 10.1. If the current transformers are ideal, the functioning of the system is straightforward. The

transformers will, however, have errors arising from both Wattmetric and magnetising current losses that cause deviation from the ideal, and the interconnections between them may have unequal impedances. This can give rise to a 'spill' current through the relay even without a fault being present, thus limiting the sensitivity that can be obtained. Figure 10.4 illustrates the equivalent circuit of the circulating current scheme. If a high impedance relay is used, then unless the relay is located at point *J* in the circuit, a current will flow through the relay even with currents I_{Pg} and I_{Ph} being identical. If a low impedance relay is used, voltage FF' will be very small, but the CT exciting currents will be unequal due to the unequal burdens and relay current I_R will still be non-zero.

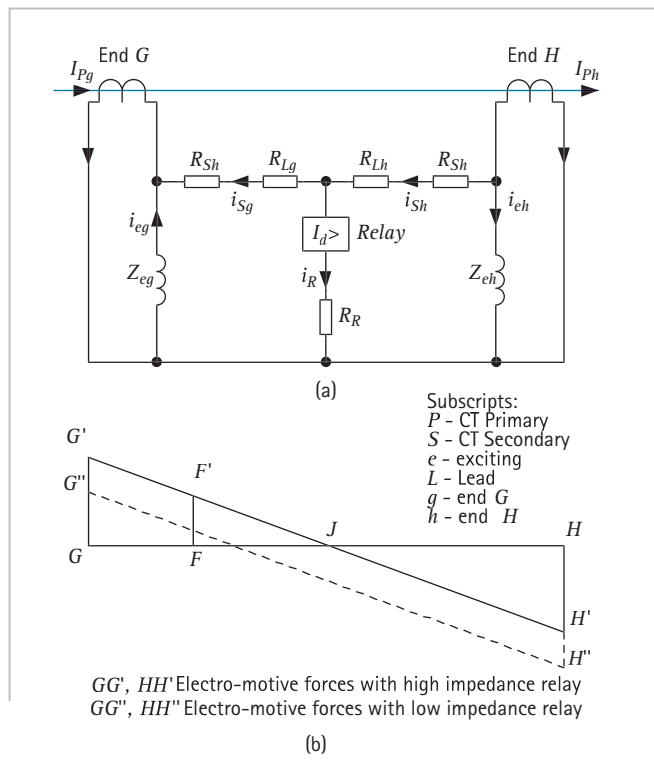


Figure 10.4: Equivalent circuit of circulating current scheme

10.4.1 Transient Instability

It is shown in Section 6.4.10 that an asymmetrical current applied to a current transformer will induce a flux that is greater than the peak flux corresponding to the steady state alternating component of the current. It may take the CT into saturation, with the result that the dynamic exciting impedance is reduced and the exciting current greatly increased.

When the balancing current transformers of a unit protection system differ in excitation characteristics, or have unequal burdens, the transient flux build-ups will differ and an increased 'spill' current will result. There is a consequent risk of relay operation on a healthy circuit under transient conditions, which is clearly

unacceptable. One solution is to include a stabilising resistance in series with the relay. Details of how to calculate the value of the stabilising resistor are usually included in the instruction manuals of all relays that require one.

When a stabilising resistor is used, the relay current setting can be reduced to any practical value, the relay now being a voltage-measuring device. There is obviously a lower limit, below which the relay element does not have the sensitivity to pick up. Relay calibration can in fact be in terms of voltage. For more details, see reference [10.2].

10.4.2 Bias

The 'spill' current in the relay arising from these various sources of error is dependent on the magnitude of the through current, being negligible at low values of through-current but sometimes reaching a disproportionately large value for more severe faults. Setting the operating threshold of the protection above the maximum level of spill current produces poor sensitivity. By making the differential setting approximately proportional to the fault current, the low-level fault sensitivity is greatly improved. Figure 10.5 illustrates a typical bias characteristic for a modern relay that overcomes the problem. At low currents, the bias is small, thus enabling the relay to be made sensitive. At higher currents, such as would be obtained from inrush or through fault conditions, the bias used is higher, and thus the spill current required to cause operation is higher. The relay is therefore more tolerant of spill current at higher fault currents and therefore less likely to maloperate, while still being sensitive at lower current levels.

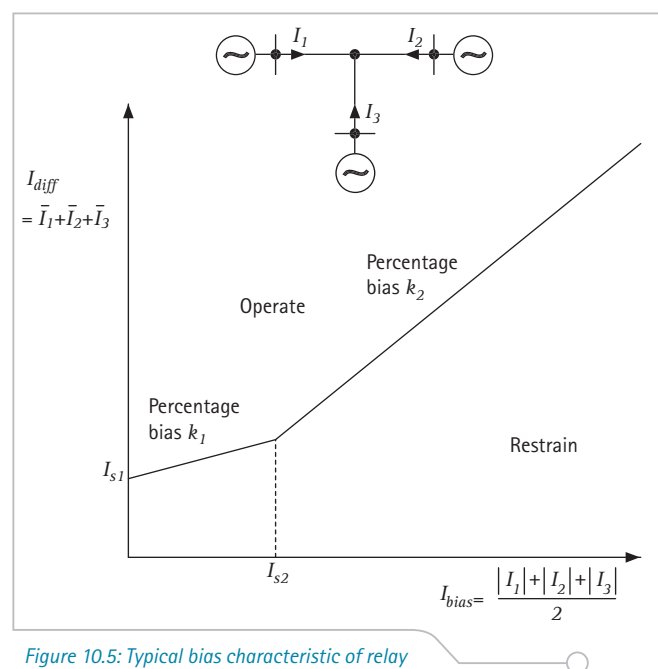


Figure 10.5: Typical bias characteristic of relay

10.5 BALANCED VOLTAGE SYSTEM

This section is included for historical reasons, mainly because of the number of such schemes still to be found in service – for new installations it has been almost completely superseded by circulating current schemes. It is the dual of the circulating current protection, and is summarised in Figure 10.2 as used in the 'Translay H04' scheme.

With primary through current, the secondary e.m.f.'s of the current transformers are opposed, and provide no current in the interconnecting pilot leads or the series connected relays. An in-zone fault leads to a circulating current condition in the CT secondaries and hence to relay operation.

An immediate consequence of the arrangement is that the current transformers are in effect open-circuited, as no secondary current flows for any primary through-current conditions. To avoid excessive saturation of the core and secondary waveform distortion, the core is provided with non-magnetic gaps sufficient to absorb the whole primary m.m.f. at the maximum current level, the flux density remaining within the linear range. The secondary winding therefore develops an e.m.f. and can be regarded as a voltage source. The shunt reactance of the transformer is relatively low, so the device acts as a transformer loaded with a reactive shunt; hence the American name of transactor. The equivalent circuit of the system is as shown in Figure 10.6.

The series connected relays are of relatively high impedance; because of this the CT secondary winding resistances are not of great significance and the pilot resistance can be moderately large without significantly affecting the operation of the system. This is why the scheme was developed for feeder protection.

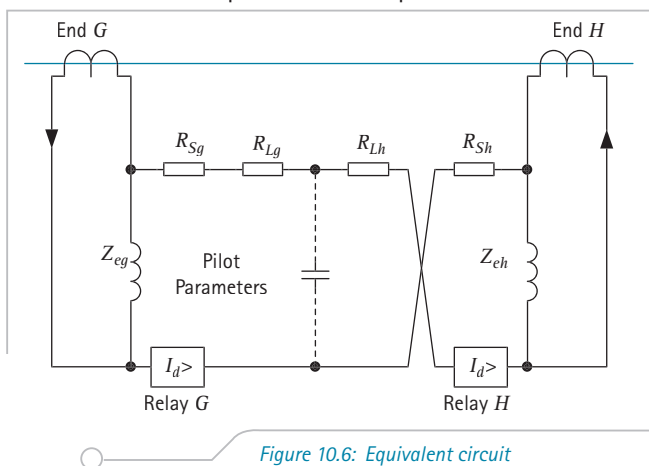


Figure 10.6: Equivalent circuit for balanced voltage system

10.5.1 Stability Limit of the Voltage Balance System

Unlike normal current transformers, transactors are not subject to errors caused by the progressive build-up of

exciting current, because the whole of the primary current is expended as exciting current. In consequence, the secondary e.m.f. is an accurate measure of the primary current within the linear range of the transformer. Provided the transformers are designed to be linear up to the maximum value of fault current, balance is limited only by the inherent limit of accuracy of the transformers, and as a result of capacitance between the pilot cores. A broken line in the equivalent circuit shown in Figure 10.6 indicates such capacitance. Under through-fault conditions the pilots are energised to a proportionate voltage, the charging current flowing through the relays. The stability ratio that can be achieved with this system is only moderate and a bias technique is used to overcome the problem.

10.6 SUMMATION ARRANGEMENTS

Schemes have so far been discussed as though they were applied to single-phase systems. A polyphase system could be provided with independent protection for each phase. Modern digital or numerical relays communicating via fibre-optic links operate on this basis, since the amount of data to be communicated is not a major constraint. For older relays, use of this technique over pilot wires may be possible for relatively short distances, such as would be found with industrial and urban power distribution systems. Clearly, each phase would require a separate set of pilot wires if the protection was applied on a per phase basis. The cost of providing separate pilot-pairs and also separate relay elements per phase is generally prohibitive. Summation techniques can be used to combine the separate phase currents into a single relaying quantity for comparison over a single pair of pilot wires. For details of such techniques, see reference [10.2].

10.7 EXAMPLES OF ELECTROMECHANICAL AND STATIC UNIT PROTECTION SYSTEMS

As mentioned above, the basic balanced voltage principle of protection evolved to biased protection systems. Several of these have been designed, some of which appear to be quite different from others. These dissimilarities are, however, superficial. A number of these systems that are still in common use are described below.

10.7.1 'Translay' Balanced Voltage Electromechanical System

A typical biased, electromechanical balanced voltage system, trade name 'Translay', still giving useful service on distribution systems is shown in Figure 10.7.

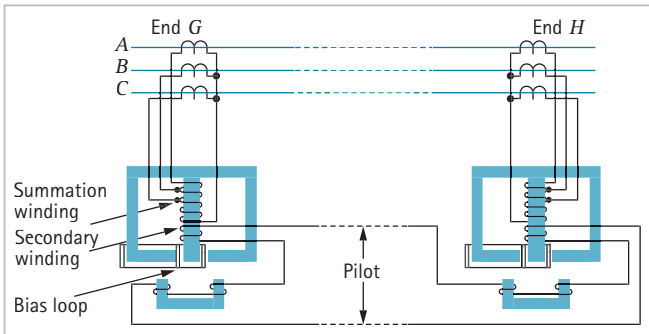


Figure 10.7: Typical biased electromechanical differential protection system.

The electromechanical design derives its balancing voltages from the transactor incorporated in the measuring relay at each line end. The latter are based on the induction-type meter electromagnet as shown in Figure 10.7.

The upper magnet carries a summation winding to receive the output of the current transformers, and a secondary winding which delivers the reference e.m.f. The secondary windings of the conjugate relays are interconnected as a balanced voltage system over the pilot channel, the lower electromagnets of both relays being included in this circuit.

Through current in the power circuit produces a state of balance in the pilot circuit and zero current in the lower electromagnet coils. In this condition, no operating torque is produced.

An in-zone fault causing an inflow of current from each end of the line produces circulating current in the pilot circuit and the energisation of the lower electromagnets. These co-operate with the flux of the upper electromagnets to produce an operating torque in the discs of both relays. An infeed from one end only will result in relay operation at the feeding end, but no operation at the other, because of the absence of upper magnet flux.

Bias is produced by a copper shading loop fitted to the pole of the upper magnet, thereby establishing a Ferraris motor action that gives a reverse or restraining torque proportional to the square of the upper magnet flux value.

Typical settings achievable with such a relay are:

- Least sensitive earth fault - 40% of rating
- Least sensitive phase-phase fault - 90% of rating
- Three-phase fault - 52% of rating

10.7.2 Static Circulating Current

Unit Protection System – 'Translay 'S' '

A typical static modular pilot wire unit protection system operating on the circulating current principle is shown in Figure 10.8. This uses summation transformers with a neutral section that is tapped, to provide alternative earth fault sensitivities. Phase comparators tuned to the power frequency are used for measurement and a restraint circuit gives a high level of stability for through faults and transient charging currents. High-speed operation is obtained with moderately sized current transformers and where space for current transformers is limited and where the lowest possible operating time is not essential, smaller current transformers may be used. This is made possible by a special adjustment (K_f) by which the operating time of the differential protection can be selectively increased if necessary, thereby enabling the use of current transformers having a correspondingly decreased knee-point voltage, whilst ensuring that through-fault stability is maintained to greater than 50 times the rated current.

Internal faults give simultaneous tripping of relays at both ends of the line, providing rapid fault clearance irrespective of whether the fault current is fed from both line ends or from only one line end.

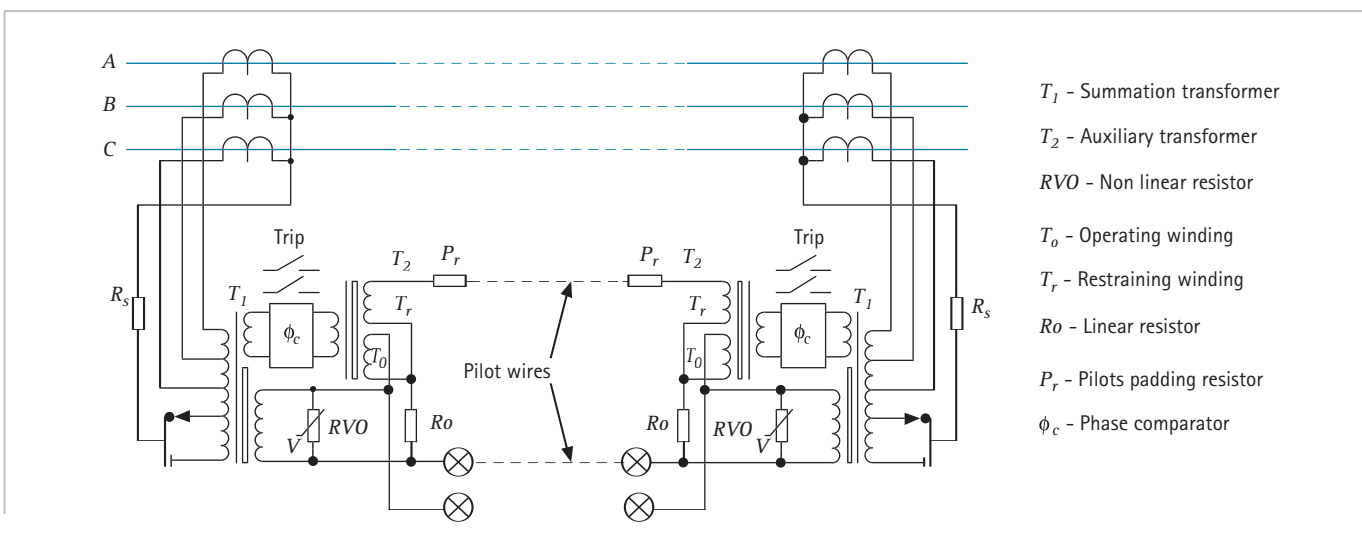


Figure 10.8: Typical static circulating current feeder unit protection circuit diagram

- T_1 - Summation transformer
- T_2 - Auxiliary transformer
- RVO - Non linear resistor
- T_o - Operating winding
- T_r - Restraining winding
- R_o - Linear resistor
- P_r - Pilots padding resistor
- ϕ_c - Phase comparator

10.8 DIGITAL/NUMERICAL CURRENT DIFFERENTIAL PROTECTION SYSTEMS

A digital or numerical unit protection relay may typically provide phase-segregated current differential protection. This means that the comparison of the currents at each relay is done on a per phase basis. For digital data communication between relays, it is usual that a direct optical connection is used (for short distances) or a multiplexed link. Link speeds of up to 64kbit/s (56kbit/s in N. America) are normal. Through current bias is typically applied to provide through fault stability in the event of CT saturation. A dual slope bias technique (Figure 10.5) is used to enhance stability for through faults. A typical trip criterion is as follows:

For $|I_{bias}| < I_{s2}$

$$|I_{diff}| < k_1 |I_{bias}| + I_{s1}$$

For $|I_{bias}| < I_{s2}$

$$|I_{diff}| < k_2 |I_{bias}| - (k_2 - k_1) I_{s2} + I_{s1}$$

Once the relay at one end of the protected section has determined that a trip condition exists, an intertrip signal is transmitted to the relay at the other end. Relays that are supplied with information on line currents at all ends of the line may not need to implement intertripping facilities. However, it is usual to provide intertripping in any case to ensure the protection operates in the event of any of the relays detecting a fault.

A facility for vector/ratio compensation of the measured currents, so that transformer feeders can be included in the unit protection scheme without the use of interposing CT's or defining the transformer as a separate zone increases versatility. Any interposing CT's required are implemented in software. Maloperation on transformer inrush is prevented by second harmonic detection. Care must be taken if the transformer has a wide-ratio on-load tap changer, as this results in the current ratio departing from nominal and may cause maloperation, depending on the sensitivity of the relays. The initial bias slope should be set taking this into consideration.

Tuned measurement of power frequency currents provides a high level of stability with capacitance inrush currents during line energisation. The normal steady-state capacitive charging current can be allowed for if a voltage signal can be made available and the susceptance of the protected zone is known.

Where an earthed transformer winding or earthing transformer is included within the zone of protection, some form of zero sequence current filtering is required. This is because there will be an in-zone source of zero sequence current for an external earth fault. The differential protection will see zero sequence differential current for an external fault and it could incorrectly

operate as a result. In older protection schemes, the problem was eliminated by delta connection of the CT secondary windings. For a digital or numerical relay, a selectable software zero sequence filter is typically employed.

The problem remains of compensating for the time difference between the current measurements made at the ends of the feeder, since small differences can upset the stability of the scheme, even when using fast direct fibre-optic links. The problem is overcome by either time synchronisation of the measurements taken by the relays, or calculation of the propagation delay of the link continuously.

10.8.1 Time Synchronisation of Relays

Fibre-optic media allow direct transmission of the signals between relays for distances of up to several km without the need for repeaters. For longer distances repeaters will be required. Where a dedicated fibre pair is not available, multiplexing techniques can be used. As phase comparison techniques are used on a per phase basis, time synchronisation of the measurements is vitally important. This requires knowledge of the transmission delay between the relays. Four techniques are possible for this:

- a. assume a value
- b. measurement during commissioning only
- c. continuous online measurement
- d. GPS time signal

Method (a) is not used, as the error between the assumed and actual value will be too great.

Method (b) provides reliable data if direct communication between relays is used. As signal propagation delays may change over a period of years, repeat measurements may be required at intervals and relays re-programmed accordingly. There is some risk of maloperation due to changes in signal propagation time causing incorrect time synchronisation between measurement intervals. The technique is less suitable if rented fibre-optic pilots are used, since the owner may perform circuit re-routing for operational reasons without warning, resulting in the propagation delay being outside of limits and leading to scheme maloperation. Where re-routing is limited to a few routes, it may be possible to measure the delay on all routes and pre-program the relays accordingly, with the relay digital inputs and ladder logic being used to detect changes in route and select the appropriate delay accordingly.

Method (c), continuous sensing of the signal propagation delay, is a robust technique. One method of achieving this is shown in Figure 10.9.

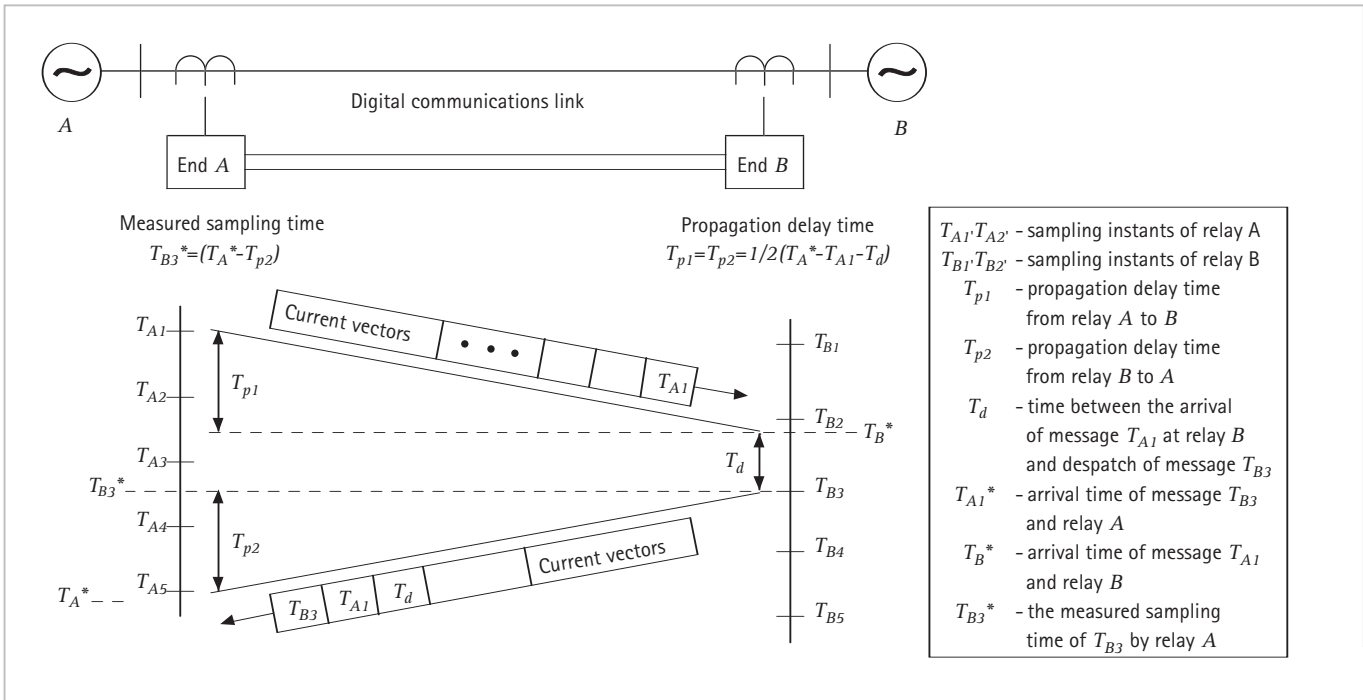


Figure 10.9: Signal propagation delay measurement

Relays A and B sample signals at time $T_{A1}, T_{A2} \dots$ and $T_{B1}, T_{B2} \dots$ respectively. The times will not be coincident, even if they start coincidentally, due to slight differences in sampling frequencies. At time T_{A1} relay A transmits its data to relay B, containing a time tag and other data. Relay B receives it at time $T_{A1} + T_{p1}$ where T_{p1} is the propagation time from relay A to relay B. Relay B records this time as time T_{B1}^* . Relay B also sends messages of identical format to relay A. It transmits such a message at time T_{B3} , received by relay A at time $T_{B3} + T_{p2}$ (say time T_{A2}^*), where T_{p2} is the propagation time from relay B to relay A. The message from relay B to relay A includes the time T_{B3} , the last received time tag from relay A (T_{A1}) and the delay time between the arrival time of the message from A (T_{B1}^*) and T_{B3} – call this the delay time T_d . The total elapsed time is therefore:

$$(T_{A2}^* - T_{A1}) = (T_d + T_{p1} + T_{p2})$$

If it is assumed that $T_{p1} = T_{p2}$, then the value of T_{p1} and T_{p2} can be calculated, and hence also T_{B3} . The relay B measured data as received at relay A can then be adjusted to enable data comparison to be performed. Relay B performs similar computations in respect of the data received from relay A (which also contains similar time information). Therefore, continuous measurement of the propagation delay is made, thus reducing the possibility of maloperation due to this cause to a minimum. Comparison is carried out on a per-phase basis, so signal transmission and the calculations are required for each phase. A variation of this technique is available that can cope with unequal propagation delays in the two

communication channels under well-defined conditions. The technique can also be used with all types of pilots, subject to provision of appropriate interfacing devices.

Method (d) is also a robust technique. It involves both relays being capable of receiving a time signal from a GPS satellite. The propagation delay on each communication channel is no longer required to be known or calculated as both relays are synchronised to a common time signal. For the protection scheme to meet the required performance in respect of availability and maloperation, the GPS signal must be capable of reliable receipt under all atmospheric conditions. There is extra satellite signal receiving equipment required at both ends of the line, which implies extra cost.

The minimum setting that can be achieved with such techniques while ensuring good stability is 20% of CT primary current.

10.8.2 Application to Mesh Corner and 1 1/2 Breaker Switched Substations

These substation arrangements are quite common, and the arrangement for the latter is shown in Figure 10.10. Problems exist in protecting the feeders due to the location of the line CT's, as either Bus 1 or Bus 2 or both can supply the feeder. Two alternatives are used to overcome the problem, and they are illustrated in the Figure. The first is to common the line CT inputs (as shown for Feeder A) and the alternative is to use a second set of CT inputs to the relay (as shown for Feeder B).

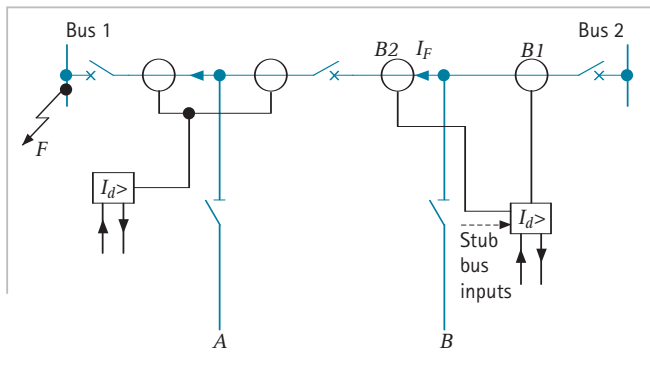


Figure 10.10: Breaker and a half switched substation

In the case of a through fault as shown, the relay connected to Feeder A theoretically sees no unbalance current, and hence will be stable. However, with the line disconnect switch open, no bias is produced in the relay, so CT's need to be well matched and equally loaded if maloperation is to be avoided.

For Feeder B, the relay also theoretically sees no differential current, but it will see a large bias current even with the line disconnect switch open. This provides a high degree of stability, in the event of transient asymmetric CT saturation. Therefore, this technique is preferred.

Sensing of the state of the line isolator through auxiliary contacts enables the current values transmitted to and received from remote relays to be set to zero when the isolator is open. Hence, stub-bus protection for the energised part of the bus is then possible, with any fault resulting in tripping of the relevant CB.

10.9 CARRIER UNIT PROTECTION SCHEMES

In earlier sections, the pilot links between relays have been treated as an auxiliary wire circuit that interconnects relays at the boundaries of the protected zone. In many circumstances, such as the protection of longer line sections or where the route involves installation difficulties, it is too expensive to provide an auxiliary cable circuit for this purpose, and other means are sought.

In all cases (apart from private pilots and some short rented pilots) power system frequencies cannot be transmitted directly on the communication medium. Instead a relaying quantity may be used to vary the higher frequency associated with each medium (or the light intensity for fibre-optic systems), and this process is normally referred to as modulation of a carrier wave. Demodulation or detection of the variation at a remote receiver permits the relaying quantity to be reconstituted for use in conjunction with the relaying quantities derived locally, and forms the basis for all carrier systems of unit protection.

Carrier systems are generally insensitive to induced

power system currents since the systems are designed to operate at much higher frequencies, but each medium may be subjected to noise at the carrier frequencies that may interfere with its correct operation. Variations of signal level, restrictions of the bandwidth available for relaying and other characteristics unique to each medium influence the choice of the most appropriate type of scheme. Methods and media for communication are discussed in Chapter 8.

10.10 CURRENT DIFFERENTIAL SCHEME – ANALOGUE TECHNIQUES

The carrier channel is used in this type of scheme to convey both the phase and magnitude of the current at one relaying point to another for comparison with the phase and magnitude of the current at that point. Transmission techniques may use either voice frequency channels using FM modulation or A/D converters and digital transmission. Signal propagation delays still need to be taken into consideration by introducing a deliberate delay in the locally derived signal before a comparison with the remote signal is made.

A further problem that may occur concerns the dynamic range of the scheme. As the fault current may be up to 30 times the rated current, a scheme with linear characteristics requires a wide dynamic range, which implies a wide signal transmission bandwidth. In practice, bandwidth is limited, so either a non-linear modulation characteristic must be used or detection of fault currents close to the setpoint will be difficult.

10.10.1 Phase Comparison Scheme

The carrier channel is used to convey the phase angle of the current at one relaying point to another for comparison with the phase angle of the current at that point.

The principles of phase comparison are illustrated in Figure 10.11. The carrier channel transfers a logic or 'on/off' signal that switches at the zero crossing points of the power frequency waveform. Comparison of a local logic signal with the corresponding signal from the remote end provides the basis for the measurement of phase shift between power system currents at the two ends and hence discrimination between internal and through faults.

Current flowing above the set threshold results in turn-off of the carrier signal. The protection operates if gaps in the carrier signal are greater than a set duration – the phase angle setting of the protection.

Load or through fault currents at the two ends of a protected feeder are in antiphase (using the normal relay convention for direction), whilst during an internal fault the (conventional) currents tend towards the in-phase

condition. Hence, if the phase relationship of through fault currents is taken as a reference condition, internal faults cause a phase shift of approximately 180° with respect to the reference condition.

Phase comparison schemes respond to any phase shift from the reference conditions, but tripping is usually permitted only when the phase shift exceeds an angle of typically 30 to 90 degrees, determined by the time delay setting of the measurement circuit, and this angle is usually referred to as the Stability Angle. Figure 10.12 is a polar diagram that illustrates the discrimination characteristics that result from the measurement techniques used in phase comparison schemes.

Since the carrier channel is required to transfer only

binary information, the techniques associated with sending teleprotection commands. Blocking or permissive trip modes of operation are possible, however Figure 10.11 illustrates the more usual blocking mode, since the comparator provides an output when neither squarer is at logic '1'. A permissive trip scheme can be realised if the comparator is arranged to give an output when both squarers are at logic '1'. Performance of the scheme during failure or disturbance of the carrier channel and its ability to clear single-end-fed faults depends on the mode of operation, the type and function of fault detectors or starting units, and the use of any additional signals or codes for channel monitoring and transfer tripping.

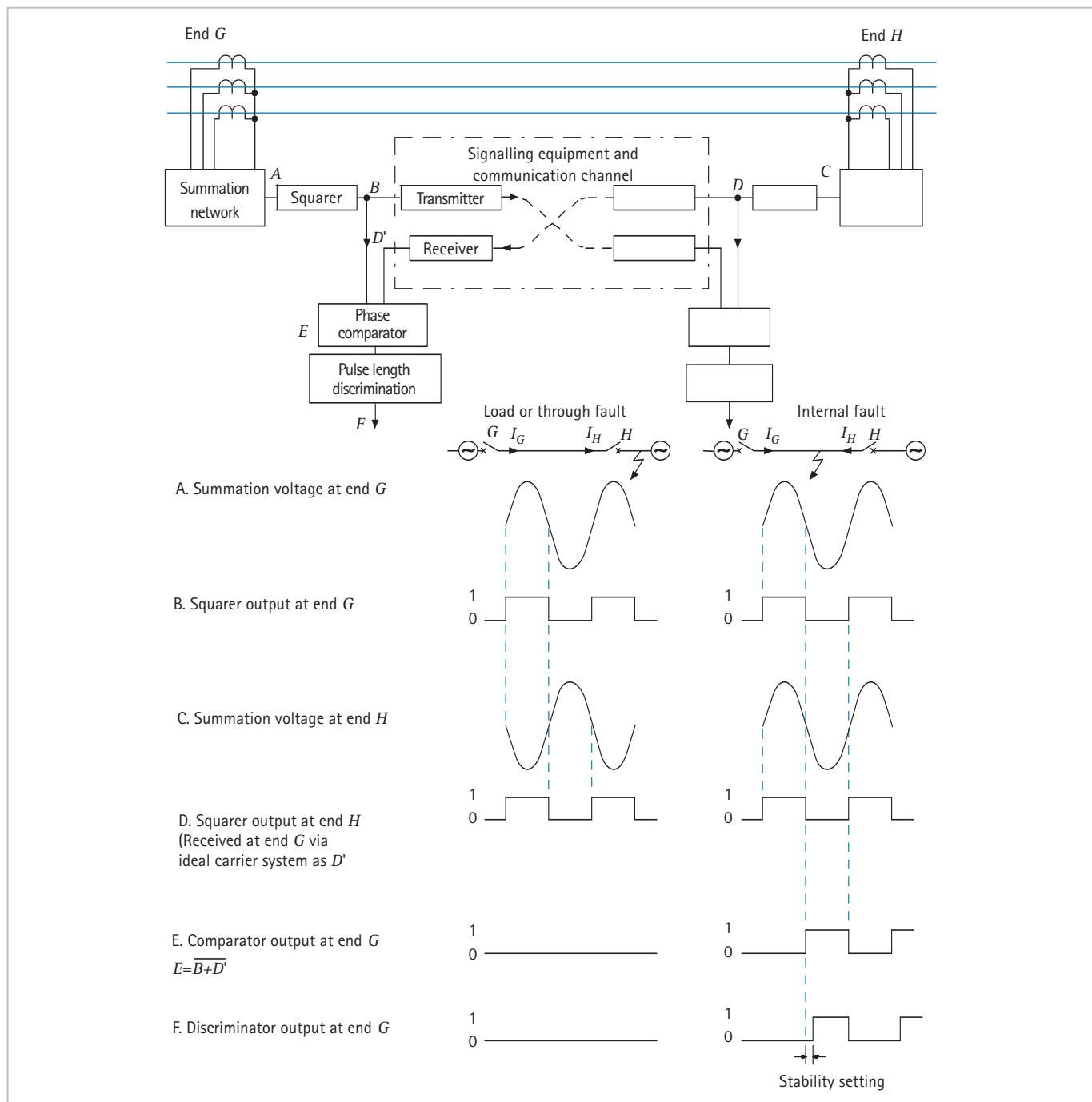


Figure 10.11: Principles of phase comparison protection.

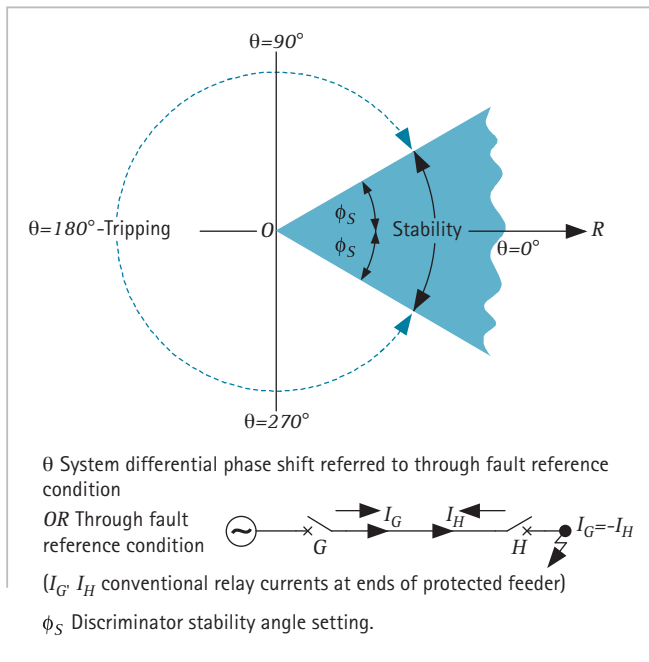


Figure 10.12: Polar diagram for phase comparison scheme

Signal transmission is usually performed by voice frequency channels using frequency shift keying (FSK) or PLC techniques.

Voice frequency channels involving FSK use two discrete frequencies either side of the middle of the voice band. This arrangement is less sensitive to variations in delay or frequency response than if the full bandwidth was used. Blocking or permissive trip modes of operation may be implemented. In addition to the two frequencies used for conveying the squarer information, a third tone is often used, either for channel monitoring or transfer tripping dependent on the scheme.

For a sensitive phase comparison scheme, accurate compensation for channel delay is required. However, since both the local and remote signals are logic pulses, simple time delay circuits can be used, in contrast to the analogue delay circuitry usually required for current differential schemes.

The principles of the Power Line Carrier channel technique are illustrated in Figure 10.13. The scheme operates in the blocking mode. The 'squarer' logic is used directly to turn a transmitter 'on' or 'off' at one end, and the resultant burst (or block) of carrier is coupled to and propagates along the power line which is being protected to a receiver at the other end. Carrier signals above a threshold are detected by the receiver, and hence produce a logic signal corresponding to the block of carrier. In contrast to Figure 10.11, the signalling system is a 2-wire rather than 4-wire arrangement, in which the local transmission is fed directly to the local receiver along with any received signal. The transmitter frequencies at

both ends are nominally equal, so the receiver responds equally to blocks of carrier from either end. Through-fault current results in transmission of blocks of carrier from both ends, each lasting for half a cycle, but with a phase displacement of half a cycle, so that the composite signal is continuously above the threshold level and the detector output logic is continuously '1'. Any phase shift relative to the through fault condition produces a gap in the composite carrier signal and hence a corresponding '0' logic level from the detector. The duration of the logic '0' provides the basis for discrimination between internal and external faults, tripping being permitted only when a time delay setting is exceeded. This delay is usually expressed in terms of the corresponding phase shift in degrees at system frequency ϕ_s in Figure 10.12.

The advantages generally associated with the use of the power line as the communication medium apply namely, that a power line provides a robust, reliable, and low-loss interconnection between the relaying points. In addition dedicated 'on/off' signalling is particularly suited for use in phase comparison blocking mode schemes, as signal attenuation is not a problem. This is in contrast to permissive or direct tripping schemes, where high power output or boosting is required to overcome the extra attenuation due to the fault.

The noise immunity is also very good, making the scheme very reliable. Signal propagation delay is easily allowed for in the stability angle setting, making the scheme very sensitive as well.

10.11 PHASE COMPARISON PROTECTION SCHEME CONSIDERATIONS

One type of unit protection that uses carrier techniques for communication between relays is phase comparison protection. Communication between relays commonly uses PLCC or frequency modulated carrier modem techniques. There are a number of considerations that apply only to phase comparison protection systems, which are discussed in this section.

10.11.1 Lines with Shunt Capacitance

A problem can occur with the shunt capacitance current that flows from an energising source. Since this current is in addition to the load current that flows out of the line, and typically leads it by more than 90° , significant differential phase shifts between the currents at the ends of the line can occur, particularly when load current is low.

The system differential phase shift may encroach into the tripping region of the simple discriminator characteristic, regardless of how large the stability angle setting may be. Figure 10.14 illustrates the effect and indicates techniques that are commonly used to ensure stability.

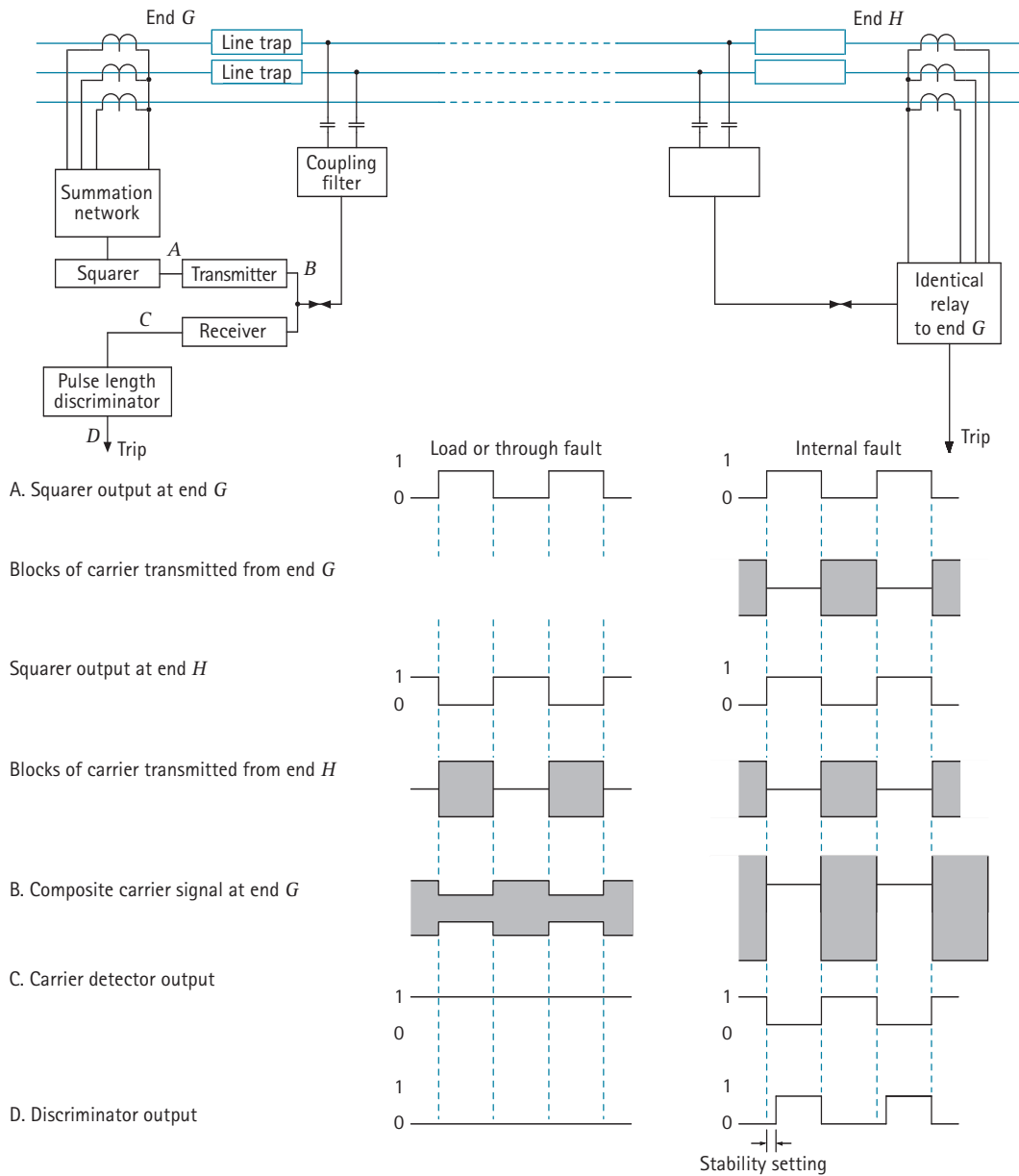
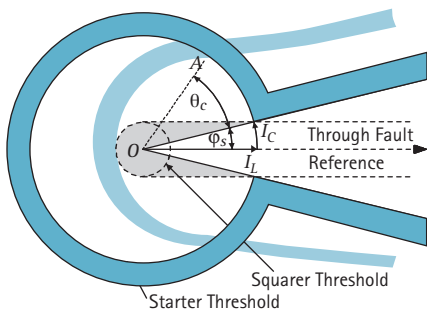


Figure 10.13: Principles of power line carrier phase comparison



- Limits of differential phase shift due to capacitive current I_C
- Encroachment into tripping region for discriminator with stability angle setting ϕ_s
- 'Keyhole' characteristic
 Minimum starter threshold = $\frac{\text{capacitive current}}{\sin \phi_s}$
 where $\phi_s = \tan^{-1} \frac{I_C}{I_L}$
- Characteristic of system with amplitude dependent compensation $\phi_s = \text{angular compensation for current of magnitude } OA$
 $\left(2 \sin^{-1} \frac{I_C}{OA} \text{ for squarer threshold } I_C \right)$
 $I_L = \text{load current}$

Figure 10.14: Capacitive current in phase comparison schemes and techniques used to avoid instability

Operation of the discriminator can be permitted only when current is above some threshold, so that measurement of the large differential phase shifts which occur near the origin of the polar diagram is avoided. By choice of a suitable threshold and stability angle, a 'keyhole' characteristic can be provided such that the capacitive current characteristic falls within the resultant stability region. Fast resetting of the fault detector is required to ensure stability following the clearance of a through fault when the currents tend to fall towards the origin of the polar diagram.

The mark-space ratio of the squarer (or modulating) waveform can be made dependent on the current amplitude. Any decrease in the mark-space ratio will permit a corresponding differential phase shift to occur between the currents before any output is given from the comparator for measurement in the discriminator. A squarer circuit with an offset or bias can provide a

decreasing mark-space ratio at low currents, and with a suitable threshold level the extra phase shift θ_c which is permitted can be arranged to equal or exceed the phase shift due to capacitive current. At high current levels the capacitive current compensation falls towards zero and the resultant stability region on the polar diagram is usually smaller than on the keyhole characteristic, giving improvements in sensitivity and/or dependability of the scheme. Since the stability region encompasses all through-fault currents, the resetting speed of any fault detectors or starter (which may still be required for other purposes, such as the control of a normally quiescent scheme) is much less critical than with the keyhole characteristic.

10.11.2 System Tripping Angles

For the protection scheme to trip correctly on internal faults the change in differential phase shift, θ_o , from the through-fault condition taken as reference, must exceed the effective stability angle of the scheme. Hence:

$$\theta_o = \varphi_s + \theta_c \quad \dots \text{Equation 10.1}$$

where

φ_s = stability angle setting

θ_c = capacitive current compensation
(when applicable)

The currents at the ends of a transmission line I_G and I_H may be expressed in terms of magnitude and phase shift θ with respect a common system voltage.

$$I_G = |I_G| \angle \theta_G$$

$$I_H = |I_H| \angle \theta_H$$

Using the relay convention described in Section 10.2, the reference through-fault condition is

$$I_G = -I_H$$

$$\therefore I_G \angle \theta_G = -I_H \angle \theta_H = I_H \angle \theta_H \pm 180^\circ$$

$$\therefore |\theta_G - \theta_H| = 180^\circ$$

During internal faults, the system tripping angle θ_o is the differential phase shift relative to the reference condition.

$$\therefore \theta_o = 180^\circ - |\theta_G - \theta_H|$$

Substituting θ_o in Equation 10.1, the conditions for tripping are:

$$180 - |\theta_G - \theta_H| \geq \varphi_s + \theta_c$$

$$\therefore |\theta_G - \theta_H| \leq 180 - (\varphi_s + \theta_c) \quad \dots \text{Equation 10.2}$$

The term $(\varphi_s + \theta_c)$ is the effective stability angle setting of the scheme. Substituting a typical value of 60° in Equation 10.2. gives the tripping condition as

$$|\theta_G - \theta_H| \leq 120^\circ \quad \dots \text{Equation 10.3}$$

In the absence of pre-fault load current, the voltages at the two ends of a line are in phase. Internal faults are fed from both ends with fault contributions whose magnitudes and angles are determined by the position of the fault and the system source impedances. Although the magnitudes may be markedly different, the angles (line plus source) are similar and seldom differ by more than about 20° .

Hence $|\theta_G - \theta_H| \leq 20^\circ$ and the requirements of Equation 10.3 are very easily satisfied. The addition of arc or fault resistance makes no difference to the reasoning above, so the scheme is inherently capable of clearing such faults.

10.11.3 Effect of Load Current

When a line is heavily loaded prior to a fault the e.m.f.'s of the sources which cause the fault current to flow may be displaced by up to about 50° , that is, the power system stability limit. To this the differential line and source angles of up to 20° mentioned above need to be added.

So $|\theta_G - \theta_H| \leq 70^\circ$ and the requirements of Equation 10.3 are still easily satisfied.

For three phase faults, or solid earth faults on phase-by-phase comparison schemes, through load current falls to zero during the fault and so need not be considered. For all other faults, load current continues to flow in the healthy phases and may therefore tend to increase $|\theta_G - \theta_H|$ towards the through fault reference value. For low resistance faults the fault current usually far exceeds the load current and so has little effect. High resistance faults or the presence of a weak source at one end can prove more difficult, but high performance is still possible if the modulating quantity is chosen with care and/or fault detectors are added.

10.11.4 Modulating Quantity

Phase-by-phase comparison schemes usually use phase current for modulation of the carrier. Load and fault currents are almost in antiphase at an end with a weak source. Correct performance is possible only when fault current exceeds load current, or

$$\text{for } I_F < I_L, |\theta_G - \theta_H| \approx 180^\circ$$

$$\text{for } I_F > I_L, |\theta_G - \theta_H| \approx 180^\circ \quad \dots \text{Equation 10.4}$$

where I_F = fault current contribution from weak source
 I_L = load current flowing towards weak source

To avoid any risk of failure to operate, fault detectors with a setting greater than the maximum load current may be applied, but they may limit the sensitivity of scheme. When the fault detector is not operated at one end, fault clearance invariably involves sequential tripping of the circuit breakers.

Most phase comparison schemes use summation techniques to produce a single modulating quantity, responsive to faults on any of the three phases. Phase sequence components are often used and a typical modulating quantity is:

$$I_M = MI_2 + NI_1 \quad \dots \text{Equation 10.5}$$

where

- I_1 = Positive phase sequence component
- I_2 = Negative phase sequence component
- M, N = constants

With the exception of three phase faults all internal faults give rise to negative phase sequence (NPS) currents, I_2 , which are approximately in phase at the ends of the line and therefore could form an ideal modulating quantity. In order to provide a modulating signal during three phase faults, which give rise to positive phase sequence (PPS) currents, I_1 , only, a practical modulating quantity must include some response to I_1 in addition to I_2 .

Typical values of the ratio $M: N$ exceed 5:1, so that the modulating quantity is weighted heavily in favour of NPS, and any PPS associated with load current tends to be swamped out on all but the highest resistance faults.

For a high resistance phase-earth fault, the system remains well balanced so that load current I_L is entirely positive sequence. The fault contribution I_F provides equal parts of positive, negative and zero sequence components $I_F/3$. Assuming the fault is on 'A' phase and the load is resistive, all sequence components are in phase at the infeed end G :

$$\therefore I_{mG} = NI_L + \frac{MI_{FG}}{3} + \frac{NI_{FG}}{3}$$

and

$$\theta_G \approx 0$$

At the outfeed end load current is negative,

$$\therefore I_{mH} = -NI_L + \frac{MI_{FH}}{3} + \frac{NI_{FH}}{3}$$

Now, for

$$I_{mH} > 0, \theta_H = 0, \text{ and } |\theta_G - \theta_H| = 0^\circ$$

and for

$$I_{mH} < 0, \theta_H = 180^\circ, \text{ and } |\theta_G - \theta_H| = 180^\circ$$

Hence for correct operation $I_{mH} \geq 0$

Let $I_{mH} = 0$

Then

$$I_{FH} = \frac{3I_L}{\left(\frac{M}{N} + 1\right)} = I_E \quad \dots \text{Equation 10.6}$$

The fault current in Equation 10.6 is the effective earth fault sensitivity I_E of the scheme. For the typical values of

$$M = 6 \text{ and } N = -1$$

$$\frac{M}{N} = -6$$

$$\therefore I_E = -\frac{3}{5}I_L$$

Comparing this with Equation 10.4, a scheme using summation is potentially 1.667 times more sensitive than one using phase current for modulation.

Even though the use of a negative value of M gives a lower value of I_E than if it were positive, it is usually preferred since the limiting condition of $I_m = 0$ then applies at the load infeed end. Load and fault components are additive at the outfeed end so that a correct modulating quantity occurs there, even with the lowest fault levels. For operation of the scheme it is sufficient therefore that the fault current contribution from the load infeed end exceeds the effective setting.

For faults on B or C phases, the NPS components are displaced by 120° or 240° with respect to the PPS components. No simple cancellation can occur, but instead a phase displacement is introduced. For tripping to occur, Equation 10.2 must be satisfied, and to achieve high dependability under these marginal conditions, a small effective stability angle is essential. Figure 10.15 illustrates operation near to the limits of earth fault sensitivity.

Very sensitive schemes may be implemented by using high values of $\frac{M}{N}$ but the scheme then becomes more sensitive to differential errors in NPS currents such as the unbalanced components of capacitive current or spill from partially saturated CT's.

Techniques such as capacitive current compensation and reduction of $\frac{M}{N}$ at high fault levels may be required to ensure stability of the scheme.

10.11.5 Fault Detection and Starting

For a scheme using a carrier system that continuously transmits the modulating quantity, protecting an ideal line (capacitive current=0) in an interconnected transmission system, measurement of current magnitude might be unnecessary. In practice, fault detector or starting elements are invariably provided and the scheme then becomes a permissive tripping scheme in which both the fault detector and the discriminator must operate to provide a trip output, and the fault detector may limit the sensitivity of the scheme. Requirements for the fault detectors vary according to the type of carrier channel used, mode of operation used in the

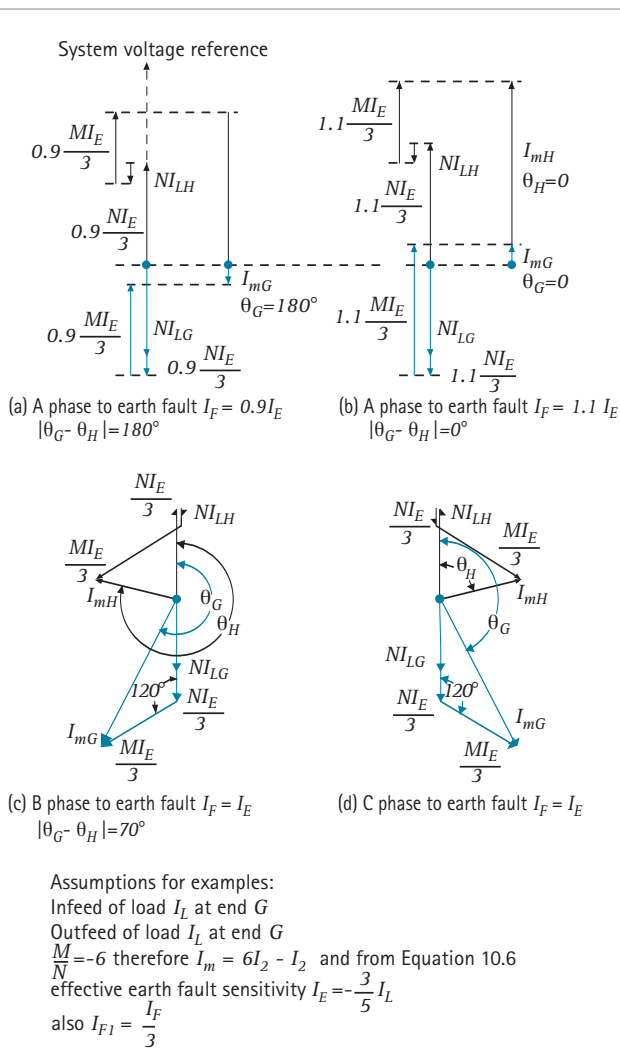


Figure 10.15: Effect of load current on differential phase shift $|\theta_G - \theta_H|$ for resistive earth faults at the effective earth fault sensitivity I_E

phase angle measurement, that is, blocking or permissive, and the features used to provide tolerance to capacitive current.

10.11.6 Normally Quiescent Power Line Carrier (Blocking Mode)

To ensure stability of through faults, it is essential that carrier transmission starts before any measurement of the width of the gap is permitted. To allow for equipment tolerances and the difference in magnitude of the two currents due to capacitive current, two starting elements are used, usually referred to as 'Low Set' and 'High Set' respectively. Low Set controls the start-up of transmission whilst High Set, having a setting typically 1.5 to 2 times that of the Low Set element, permits the phase angle measurement to proceed.

The use of impulse starters that respond to the change in current level enables sensitivities of less than rated current to be achieved. Resetting of the starters occurs naturally after a swell time or at the clearance of the fault. Dwell times and resetting characteristics must

ensure that during through faults, a High Set is never operated when a Low Set has reset and potential race conditions are often avoided by the transmitting of an unmodulated (and therefore blocking) carrier for a short time following the reset of low set; this feature is often referred to as 'Marginal Guard.'

10.11.7 Scheme without Capacitive Current Compensation

The 'keyhole' discrimination characteristic of depends on the inclusion of a fault detector to ensure that no measurements of phase angle can occur at low current levels, when the capacitive current might cause large phase shifts. Resetting must be very fast to ensure stability following the shedding of through load.

10.11.8 Scheme with Capacitive Current Compensation (Blocking Mode)

When the magnitude of the modulating quantity is less than the threshold of the squarer, transmission if it occurred, would be a continuous blocking signal. This might occur at an end with a weak source, remote from a fault close to a strong source. A fault detector is required to permit transmission only when the current exceeds the modulator threshold by some multiple (typically about 2 times) so that the effective stability angle is not excessive. For PLCC schemes, the low set element referred to in Section 10.11.6 is usually used for this purpose. If the fault current is insufficient to operate the fault detector, circuit breaker tripping will normally occur sequentially.

10.11.9 Fault Detector Operating Quantities

Most faults cause an increase in the corresponding phase current(s) so measurement of current increase could form the basis for fault detection. However, when a line is heavily loaded and has a low fault level at the outfeed end, some faults can be accompanied by a fall in current, which would lead to failure of such fault detection, resulting in sequential tripping (for blocking mode schemes) or no tripping (for permissive schemes). Although fault detectors can be designed to respond to any disturbance (increase or decrease of current), it is more usual to use phase sequence components. All unbalanced faults produce a rise in the NPS components from the zero level associated with balanced load current, whilst balanced faults produce an increase in the PPS components from the load level (except at ends with very low fault level) so that the use of NPS and PPS fault detectors make the scheme sensitive to all faults. For schemes using summation of NPS and PPS components for the modulating quantity, the use of NPS and PPS fault

detectors is particularly appropriate since, in addition to any reductions in hardware, the scheme may be characterized entirely in terms of sequence components. Fault sensitivities I_F for PPS and NPS impulse starter settings I_{1S} and I_{2S} respectively are as follows:

$$\begin{aligned} \text{Three phase fault} & I_F = I_{1S} \\ \text{Phase-phase fault} & I_F = \sqrt{3}I_{2S} \\ \text{Phase-earth fault} & I_F = 3I_{2S} \end{aligned}$$

10.12 EXAMPLES

This section gives examples of setting calculations for simple unit protection schemes. It cannot and is not intended to replace a proper setting calculation for a particular application. It is intended to illustrate the principles of the calculations required. The examples use the AREVA MiCOM P541 Current Differential relay, which has the setting ranges given in Table 10.1 for differential protection. The relay also has backup distance, high-set instantaneous, and earth-fault protection included in the basic model to provide a complete 'one-box' solution of main and backup protection.

10.12.1 Unit Protection of a Plain Feeder

The circuit to be protected is shown in Figure 10.16. It consists of a plain feeder circuit formed of an overhead line 25km long. The relevant properties of the line are:
Line voltage: 33kV

$$Z = 0.157 + j0.337\Omega/km$$

Shunt charging current = $0.065A/km$

To arrive at the correct settings, the characteristics of the relays to be applied must be considered.

The recommended settings for three of the adjustable values (taken from the relay manual) are:

$$I_{s2} = 2.0pu$$

Parameter	Setting Range
Differential Current Setting, I_{s1}	0.2 - 2.0 I_n
Bias Current Threshold Setting, I_{s2}	1-30 I_n
Lower Percentage Bias Setting, k_1	0.3-1.5
Higher Percentage Bias Setting, k_2	0.3-1.5
I_n - CT rated secondary current	

Table 10.1: Relay Setting Ranges

$$\begin{aligned} k_1 &= 30\% \\ k_2 &= 150\% \end{aligned}$$

To provide immunity from the effects of line charging current, the setting of I_{s1} must be at least 2.5 times the steady-state charging current, i.e. 4.1A or 0.01p.u., after taking into consideration the CT ratio of 400/1. The nearest available setting above this is 0.20p.u. This gives the points on the relay characteristic as shown in Figure 10.17. The minimum operating current I_{dmin} is related to the value of I_{s1} by the formula

$$I_{dmin} = (k_1 I_L + I_{s1}) / (1 - 0.5k_1)$$

for $I_{bias} < I_{s2}$

and

$$I_{dmin} = (k_2 I_L - (k_2 - k_1) I_{s2} + I_{s1}) / (1 - 0.5k_2)$$

for $I_{bias} > I_{s2}$

where I_L = load current

and hence the minimum operating current at no load is 0.235p.u. or 94A.

In cases where the capacitive charging current is very large and hence the minimum tripping current needs to be set to an unacceptably high value, some relays offer the facility of subtracting the charging current from the measured value. Use of this facility depends on having a suitable VT input and knowledge of the shunt capacitance of the circuit.

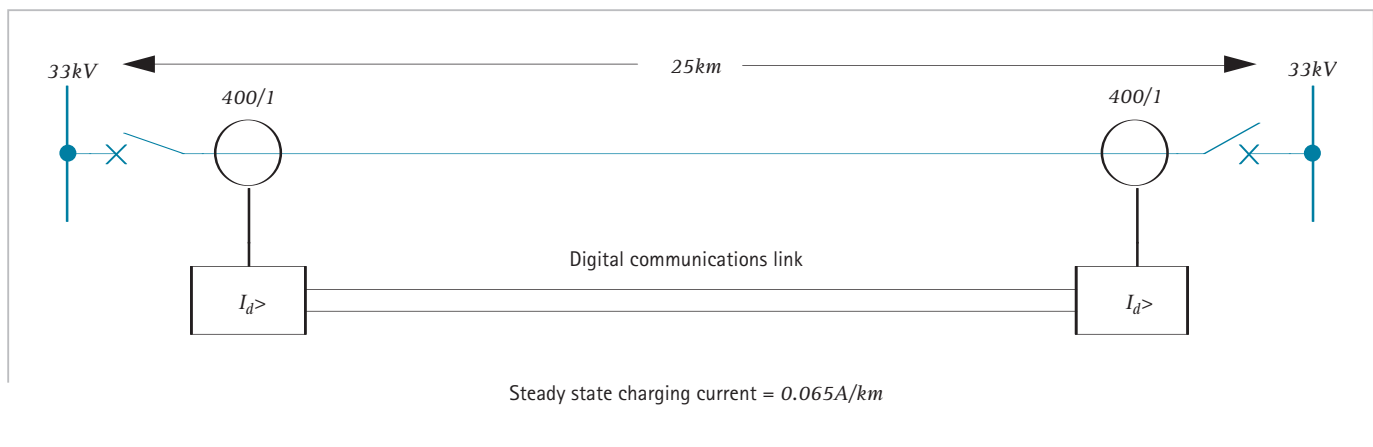


Figure 10.16: Typical plain feeder circuit

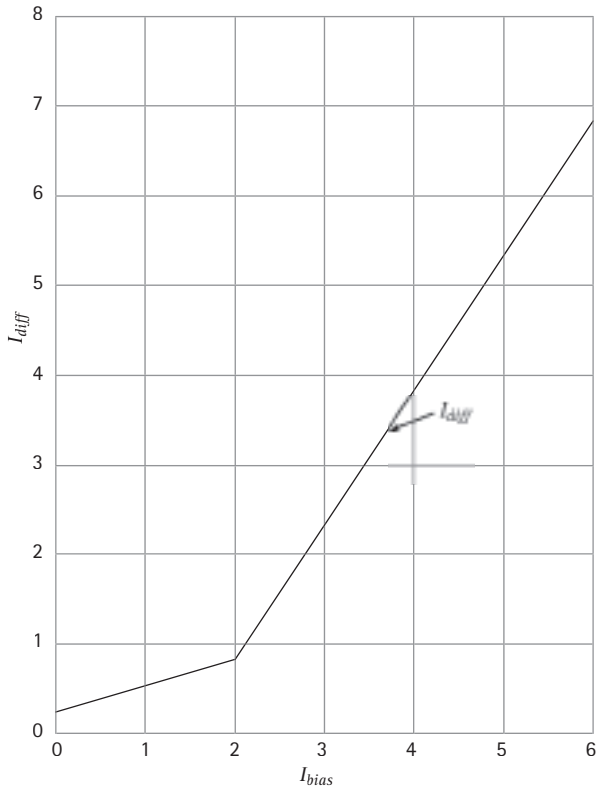


Figure 10.17: Relay characteristic; plain feeder example

10.12.2 Unit Protection of a Transformer Feeder

Figure 10.18 shows unit protection applied to a transformer feeder. The feeder is assumed to be a 100m length of cable, such as might be found in some industrial plants or where a short distance separates the 33kV and 11kV substations. While 11kV cable capacitance will exist, it can be regarded as negligible for the purposes of this example.

The delta/star transformer connection requires phase shift correction of CT secondary currents across the transformer, and in this case software equivalents of interposing CT's are used.

Since the LV side quantities lag the HV side quantities by 30°, it is necessary to correct this phase shift by using software CT settings that produce a 30° phase shift. There are two obvious possibilities:

- a. HV side: *Yd1*
LV side: *Yy0*
- b. HV side: *Yy0*
LV side: *Yd11*

Only the second combination is satisfactory, since only this one provides the necessary zero-sequence current trap to avoid maloperation of the protection scheme for earth faults on the LV side of the transformer outside of the protected zone.

Ratio correction must also be applied, in order to ensure that the relays see currents from the primary and secondary sides of the transformer feeder that are well balanced under full load conditions. This is not always inherently the case, due to selection of the main CT ratios.

Transformer turns ratio at nominal tap

$$= \frac{11}{33} = 0.3333$$

Required turns ratio according to the CT ratios used

$$= \frac{400/1}{1250/1} = 0.32$$

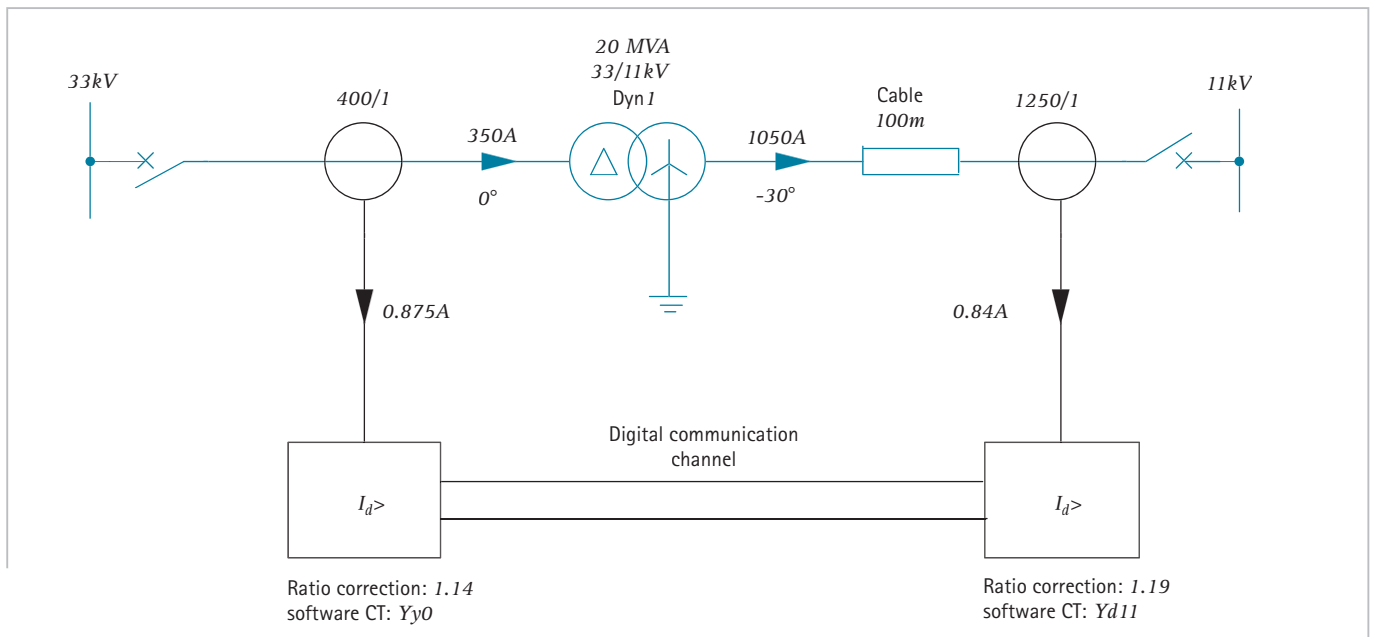


Figure 10.18: Unit protection of a transformer feeder

Spill current that will arise due to the incompatibility of the CT ratios used with the power transformer turns ratio may cause relay maloperation. This has to be eliminated by using the facility in the relay for CT ratio correction factors. For this particular relay, the correction factors are chosen such that the full load current seen by the relay software is equal to $1A$.

The appropriate correction factors are:

$$\text{HV: } 400/350 = 1.14$$

$$\text{LV: } 1250/1050 = 1.19$$

where:

$$\text{transformer rated primary current} = 350A$$

$$\text{transformer rated secondary current} = 1050A$$

With the line charging current being negligible, the following relay settings are then suitable, and allow for transformer efficiency and mismatch due to tap-changing:

$$I_{S1} = 20\% \text{ (minimum possible)}$$

$$I_{S1} = 20\%$$

$$k_1 = 30\%$$

$$k_2 = 150\%$$

10.13 REFERENCES

- 10.1 *Merz-Price Protective Gear*. K. Faye-Hansen and G. Harlow. IEE Proceedings, 1911.
- 10.2 *Protective Relays Application Guide – 3rd Edition*. AREVA Transmission and Distribution Protection and Control, 1987.