C10 A.C. Railway Protection

Network Protection & Automation Guide

Life Is On Schneider Electric

Chapter C10

A.C. Railway Protection

C10

1. Introduction

Many regional, urban and high-speed inter-urban rail networks worldwide are electrified, to provide the motive power for trains (Figure C10.1).

The electrification system serves as the contact interface for current collection by each train, and in a.c. electrified railways as the means to distribute power. In general, one of two philosophies are followed: an overhead catenary above the track, with power collection by a pantograph; or conductor-rail electrification, with current collection via contact shoes on a surface of a special metallic conductor laid close to the running rails. The latter arrangement is most commonly used for d.c. traction, while the former arrangement is used for a.c. and d.c. traction. Some rail routes have dual overhead and conductor-rail electrification to facilitate route sharing by different rail operators.

Overhead catenaries are generally considered to be safer, as they are above the track, out of reach of rail personnel and the public. They are the only way in which a traction feed at high voltages can be engineered. They provide a single-phase a.c. supply with a voltage in the range of 11kV-50kV with respect to the running rails, although 1.5kV and 3kV d.c. catenaries are predominant in some countries. When a conductor-rail system is used, the supply voltage is generally 600V to 1700V d.c.

This chapter covers protection associated with HV overhead a.c. catenary electrification. Due to the nature of many rail routes and the limited electrical clearances (especially where an existing non-electrified route is to be electrified), catenary faults are common. A typical fault rate is one fault per year per route kilometre of track. The relatively high fault rate, coupled with the high mechanical tension in the contact wire (typically 6-20kN) demands fast fault clearance. Should a fault not be cleared quickly, the conductors that form the catenary may break due to intense overheating, with the consequent risk of further severe damage caused by moving trains and lengthy disruption to train services.

Figure C10.1:
Modern high-speed a.c. electric inter-urban train

2. Protection philosophy

The application of protection to electrical power transmission schemes is biased towards security whilst ensuring dependability only for the most severe faults within the protected circuit. Being too adventurous with the application of remote back-up protection should be avoided, since the consequences of unwanted tripping are serious.

In the case of electrified railways, there is a high probability that sustained electrical faults of any type (high resistance, remote breaker/protection failure etc.) may be associated with overhead wire damage or a faulty traction unit. Fallen live wires caused by mechanical damage or accident represent a greater safety hazard with railways, due to the higher probability of people being close by (railway personnel working on the track, or passengers). Traction unit faults are a fire hazard and a safety risk to passengers, especially in tunnels. For these reasons, there will be a bias towards dependability of back-up protection at the expense of security. The consequences of an occasional unwanted trip are far more acceptable (the control centre simply recloses the tripped CB, some trains are delayed while the control centre ensures it is safe to reclose) than the consequences of a failure to trip for a fallen wire or a traction unit fault.

3. Classical single-phase feeding

Classical single-phase a.c. railway electrification has been used since the 1920's. Earlier systems used low frequency supplies and in many countries, electrification systems using 16.7Hz and 25Hz supplies are still in use. The cost of conversion of an extensive network, with a requirement for through working of locomotives, throughout the necessary changeover period, is usually prohibitive.

Starting from Western Europe and with the influence spreading worldwide, single-phase a.c. electrification at the standard power system frequency of 50/60Hz, has become the standard.

Figure C10.2 illustrates classical 25kV feeding with booster transformers (BT).

The booster transformers are used to force the traction return current to flow in an aerially mounted return conductor, anchored to the back of the supporting masts (Figure C10.3). This arrangement limits traction current returning through the rails and earth in a large cross-sectional loop, thereby reducing electromagnetic interference with adjacent telecommunication circuits. A step-down transformer connected phase to phase across the Utility grid is generally the source of the traction supply. The electrical feed to the train is via the overhead catenary, with the return current flowing via the rails and then through the return conductor.

As the running rails are bonded to earth at regular intervals, they are nominally at earth potential. A single-pole circuit breaker is all that is required to disconnect the supply to the catenary in the event of a fault.

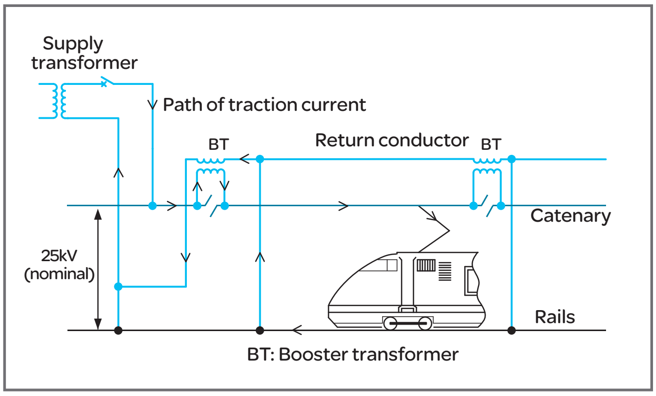

Figure C10.2: Classical 25kV feeding with booster transformers

3.1 Classical system - Feeding diagram

In practice, single-track railway lines are rare, and two or four parallel tracks are more common. The overhead line equipment is then comprised of two or four electrically independent catenaries, running in parallel. Figure C10.4 shows the feeding diagram for a typical two-track railway using a classical electrification system.

The infeed to the tracks in the 'northbound' direction is via grid transformer $T1$ at the Feeder Station (FS). The power is then distributed via catenaries A and B above the northbound and southbound tracks. At intervals, it is usual to parallel the two catenaries at paralleling/sub-sectioning substations, as illustrated in the Figure C10.4. Load current can then flow in the parallel paths, which reduces the impedance to the load and hence the line voltage drops. As the substation terminology implies, the provision of circuit breakers for each of the outgoing feeds to the catenaries also allows subsectioning – i.e. the ability to disconnect supply from sections of catenary, in the event of a fault, or to allow for maintenance. For a fault on catenary 'A' in Figure C10.4, circuit breakers A at the feeder station and at $SS1$ would be tripped to isolate the faulted catenary. The supply to the healthy sections of catenary B, C, D, E and F would be maintained.

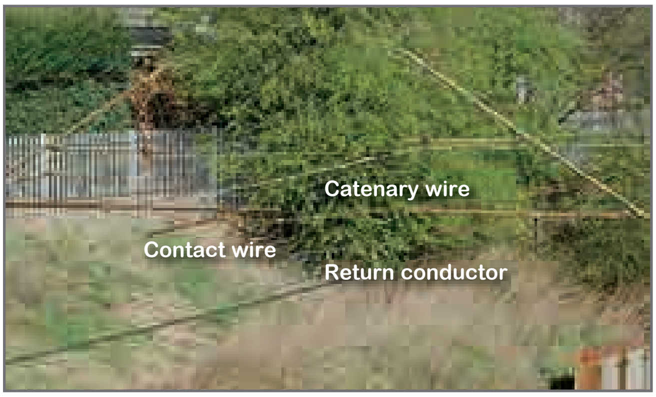

Figure C10.3: Classical overhead line construction

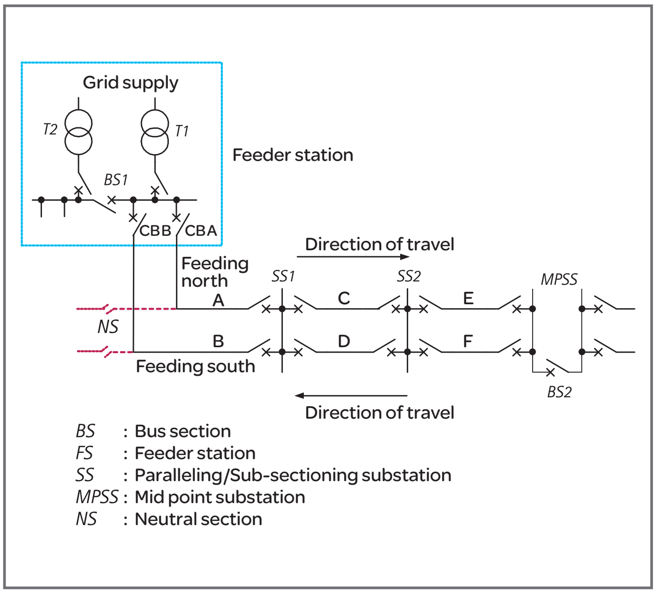

Figure C10.4: Classical 25kV feeding diagram

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3. Classical single-phase feeding

The infeed from $T1$ generally feeds only as far as the normally open bus section circuit breaker ($BS2$) at the mid-point substation ($MPSS$). Beyond the $MPSS$ there is a mirror image of the electrical arrangements $T1$ to $BS2$ shown in Figure C10.4, with the remote end feeder station often 40-60km distant from $T1$. $BS2$ must remain open during normal feeding, to prevent Utility power transfer via the single-phase catenary, or to avoid parallelling supplies that may be derived from different phase pairs of the Utility grid – e.g. Phase A-B at $T1$, and B-C at the next FS to the north. The same is true for $BS1$, which normally remains open, as the $T1$ and $T2$ feeds are generally from different phase pairs, in an attempt to balance the loading on the three phase Utility grid. The neutral section (NS) is a non-conducting section of catenary used to provide continuity of the catenary for the pantographs of motive power units while isolating electrically the sections of track. While only two (one per rail track) are shown for simplicity, separating the tracks fed by $T1$ and $T2$ at the Feeder Station, they are located at every point where electrical isolation facilities are provided.

3.2 Classical system - Protection philosophy

The grid infeed transformers are typically rated at 10 to 25MVA, with a reactance of around 10% (or 2.5 Ω when referred to the 25kV winding). Thus, even for a fault at the Feeder Station busbar, the maximum prospective short circuit current is low in comparison to a Utility system (typically only 10 times the rating of a single catenary). If a fault occurs further down the track, there will be the additional impedance of the catenary and return conductor to be added to the impedance of the fault loop. A typical loop impedance would be 0.6Ω/km (1Ω /mile). Account may have to be taken of unequal catenary impedances – for instance on a four-track railway, the catenaries for the two centre tracks have a higher impedance than those for the outer tracks due to mutual coupling effects. For a fault at the remote end of a protected section (e.g. Catenary section 'A' in Figure C10.4), the current measured at the upstream circuit breaker location (CB A at the FS) may be twice rated current. Thus at Feeder Stations, overcurrent protection can be applied, as there is a sufficient margin between the maximum continuous load current and the fault current at the remote ends of catenary sections. However, overcurrent protection is often used only as time-delayed back-up protection on railways, for the following reasons:

a. the protection needs to be discriminative, to ensure that only the two circuit breakers associated with the faulted line section are tripped. This demands that the protection should be directional, to respond only to fault current flowing into the section. At location $SS1$, for example, the protection for catenaries A and B would have to look back towards the grid infeed. For a fault close to the FS on catenary A, the remote end protection will measure only the proportion of fault current that flows via healthy catenary B, along the 'hairpin' path to $SS1$ and back along catenary A to the location of the fault. This fault current contribution may be less than rated load current (see Figure C10.5)

b. the prospective fault current levels at $SS1$, $SS2$ and $MPSS$ are progressively smaller, and the measured fault currents at these locations may be lower than rated current

c. during outages of grid supply transformers, alternative feeding may be necessary. One possible arrangement is to extend the normal feeding by closing the bus section circuit breaker at the $MPSS$. The prospective current levels for faults beyond the $MPSS$ will be much lower than normal

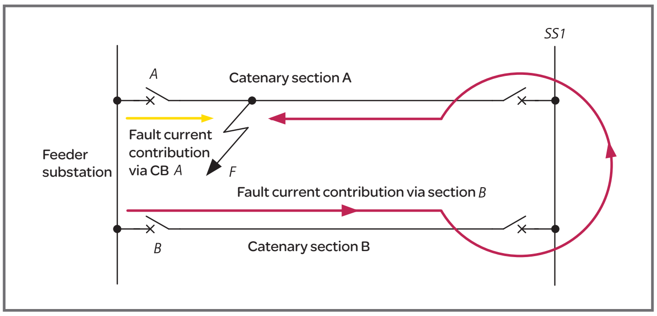

Figure C10.5: 'Hairpin' fault current contribution

Overcurrent protection is detailed in Section 5.

In addition to protection against faults, thermal protection of the catenary is required to prevent excessive contact wire sag, leading to possible dewirements. Section 4 details the principles of catenary thermal protection.

Distance protection has been the most proven method of protecting railway catenaries, due to its inherent ability to remain stable for heavy load current, whilst being able to discriminatively trip for quite low levels of fault current. For general details of distance protection, see Chapter [C3: Distance Protection]. Figure C10.5 shows how the fault current generally lags the system voltage by a greater phase angle than is usual under load conditions, and thus the impedance phase angle measurement is an important attribute of distance relays for discriminating between minimum load impedance and maximum remote fault impedance.

3.3 Distance protection zone reaches

Distance relays applied to a classical single-phase electrified railway system have two measurement inputs:

a. a catenary to rail voltage signal derived from a line or busbar connected voltage transformer

b. a track feeder current signal derived from a current transformer for the circuit breaker feeding the protected section

3. Classical single-phase feeding

Distance relays perform a vector division of voltage by current to determine the protected circuit loop impedance (Z). Typical relay characteristics are shown in the $R + jX$ impedance diagram, Figure C10.6.

Solid faults on the catenary will present impedances to the relay along the dotted line in Figure C10.6. The illustrated quadrilateral distance relay operating zones have been set with characteristic angles to match the catenary solid-fault impedance angle, which is usually 70 to 75 degrees. Two of the zones of operation have been set as directional, with the third being semi-directional to provide back-up protection. The measured fault impedance will be lower for a fault closer to the relay location, and the relay makes a trip decision when the measured fault impedance falls within its tripping zones. Three zones of protection (shown as $Z1$, $Z2$, $Z3$) are commonly applied. For each zone, the forward and resistive impedance reach settings must be optimised to avoid tripping for load current, but to offer the required catenary fault coverage. All fault impedance reaches for distance zones are calculated in polar form, $Z\angle\theta$, where Z is the reach in ohms, and θ is the line angle setting in degrees. For railway systems, where all catenaries have a similar fault impedance angle, it is often convenient to add and subtract section impedances algebraically and treat Z as a scalar quantity.

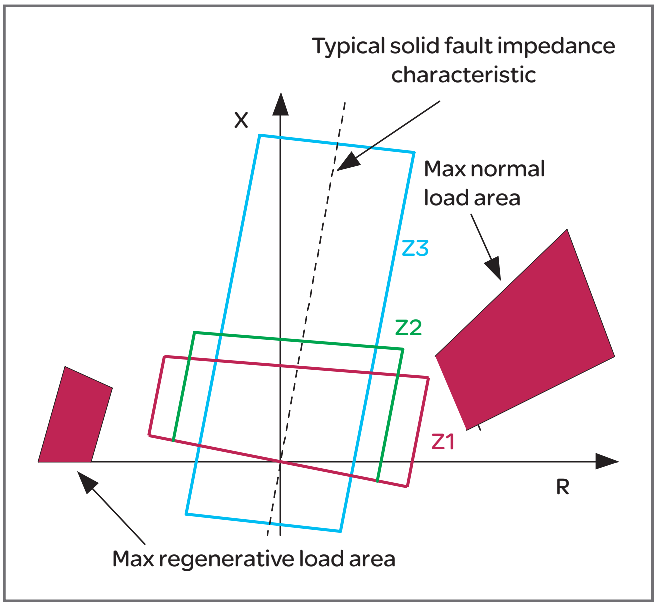

Figure C10.6:
Polar impedance plot of typical trip characteristics

Relays at all of the track sectioning substations ($SS1$, etc.) will see the reverse-looking load and regeneration areas in addition to those in the forward direction shown in Figure C10.6. The reverse-looking zones, which are mirror images of the forward-looking zones, have been omitted from the diagram for clarity.

3.3.1 Zone 1

The Zone 1 element of a distance relay is usually set to protect as much of the immediate catenary section as possible, without picking-up for faults that lie outside of the section. In such applications Zone 1 tripping does not need to be time-graded with the operation of other protection, as the Zone 1 reach ($Z1$) cannot respond to faults beyond the protected catenary section. Zone 1 tripping can be instantaneous (i.e. no intentional time delay). For an under-reaching application, the Zone 1 reach must therefore be set to account for any possible overreaching errors. These errors come from the relay, the VTs and CTs and inaccurate catenary impedance data. It is therefore recommended that the reach of the Zone 1 element is restricted to 85% of the protected catenary impedance, with the Zone 2 element set to cover the final 15%.

3.3.2 Zone 2

To allow for under-reaching errors, the Zone 2 reach ($Z2$) should be set to a minimum of 115% of the protected catenary impedance for all fault conditions. This is to guarantee coverage of the remote end not covered by Zone 1. It is often beneficial to set Zone 2 to reach further than this minimum, in order to provide faster back-up protection for uncleared downstream faults. A constraining requirement is that Zone 2 does not reach beyond the Zone 1 reach of downstream catenary protection. This principle is illustrated in Figure C10.7, for a four-track system, where the local breaker for section H has failed to trip.

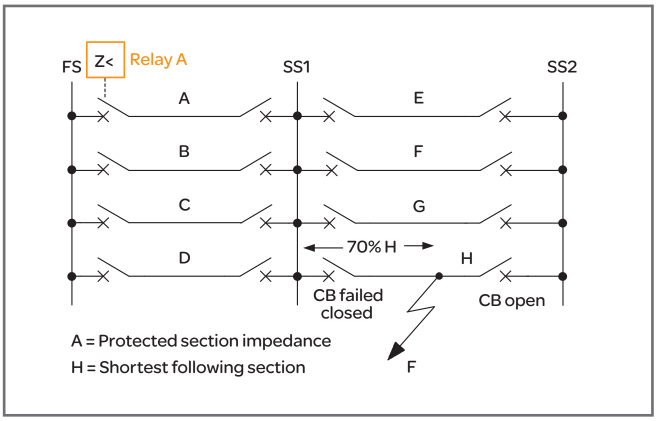

Figure C10.7:
Fault scenario for Zone 2 reach constraint (normal feeding)

In order to calculate $Z2$ for the FS circuit breaker of protected catenary 'A', a fault is imagined to occur at 70% of the shortest following section. This is the closest location that unwanted overlap could occur with $Z2$ main protection for catenary H. The value of 70% is determined by subtracting a suitable margin for measurement errors (15%) from the nominal 85% $Z1$ reach for catenary H protection.

3. Classical single-phase feeding

The apparent impedance of the fault, as viewed from relay A at location FS is then calculated, noting that any fault impedance beyond $SS1$ appears to be approximately four times its actual ohmic impedance, due to the fault current parallelling along four adjacent tracks. The setting applied to the relay is the result of this calculation, with a further 15% subtracted to allow for accommodation of any measurement errors at relay A location.

The equation for the maximum Zone 2 reach becomes:

$$Z2 = \frac{\left((Z + 0.7H) \times \frac{(A + R)}{R} \right)}{1.15} \quad \text{...Equation C10.1}$$

where:

H = impedance of shortest following section

A = impedance of protected section

R = impedance of sections B, C, D in parallel

Z = impedance of sections A, B, C, D in parallel

The possibility of current following out and back along a hairpin path to a fault has already been discussed and it is essential that the relay does not overreach under these conditions. The feeding scenario is shown in Figure C10.8.

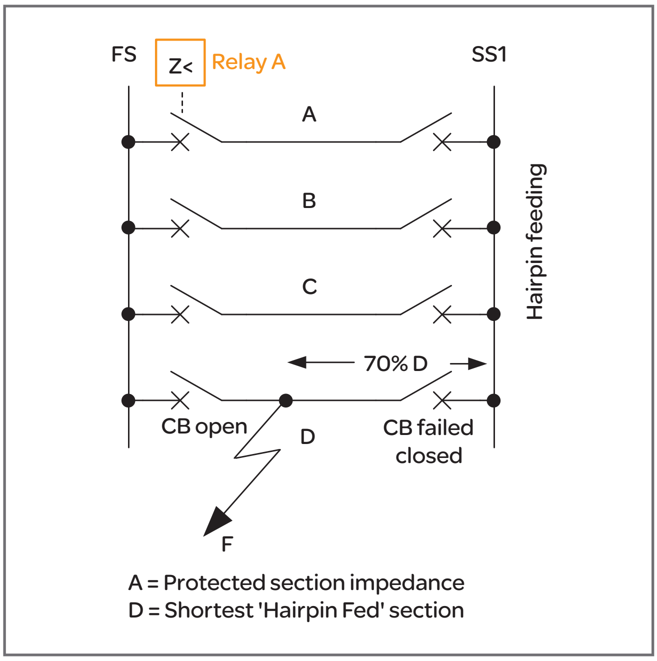

Figure C10.8:
Fault scenario for maximum Zone 2 reach (hairpin feeding)

Figure C10.8 depicts a fault that has been cleared at one end only, with the remote end breaker for section D failing to trip. The fault is assumed to be on the lowest impedance catenary, which is an important consideration when there are more than two tracks. In a four-track system, it is usual for mutual induction to cause inner (middle) track catenaries to have a characteristic impedance that is 13% higher than for the outside tracks.

The calculation principle is similar to that for normal feeding, except that now the fault current is parallelling along three (= number of tracks minus one) adjacent tracks. The three catenaries concerned are the protected catenary A, and the remainder of the healthy catenaries (R), i.e. catenaries B and C.

The equation for the maximum hairpin Zone 2 reach becomes:

$$Z2 = \frac{\left((Z + 0.7D) \times \frac{(A + R)}{R} \right)}{1.15} \quad \text{...Equation C10.2}$$

where:

D = impedance of shortest hairpin fed section

A = impedance of protected section

R = impedance of sections B and C in parallel

Z = impedance of sections A, B, C in parallel

To avoid overreaching for both normal feeding and hairpin fed faults, the lower of the two calculated impedances is used as the Zone 2 reach setting.

3.3.3 Zone 3

The Zone 3 element would usually be used to provide overall back-up protection for downstream catenary sections. The Zone 3 reach ($Z3$) should typically be set to at least 115% of the combined apparent impedance of the protected catenary plus the longest downstream catenary. Figure C10.9 shows the feeding considered:

The equation for the minimum Zone 3 reach (normal feeding) for Relay A becomes:

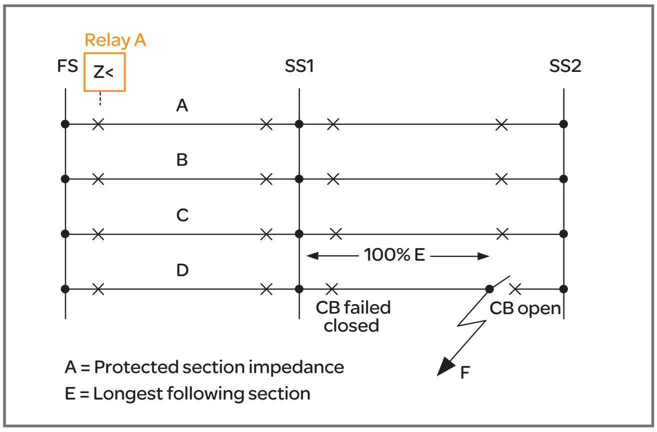

Figure C10.9:
Fault scenario for Zone 3 minimum reach (normal feeding)

3. Classical single-phase feeding

$$Z3 = 1.15 \times (Z + E) \times \left(\frac{(A + R)}{R} \right)$$ ...Equation C10.3

where:

E = impedance of longest following section

A = impedance of protected section

R = impedance of sections B, C, D in parallel

Z = impedance of sections A, B, C, D in parallel

It can be appreciated that hairpin feeding scenarios too must be considered, and this is depicted in Figure C10.10: The equation for the minimum Zone 3 reach (hairpin feeding) becomes:

$$Z3 = 1.15 \times (Z + D) \times \left(\frac{(A + R)}{R} \right)$$ ...Equation C10.4

where:

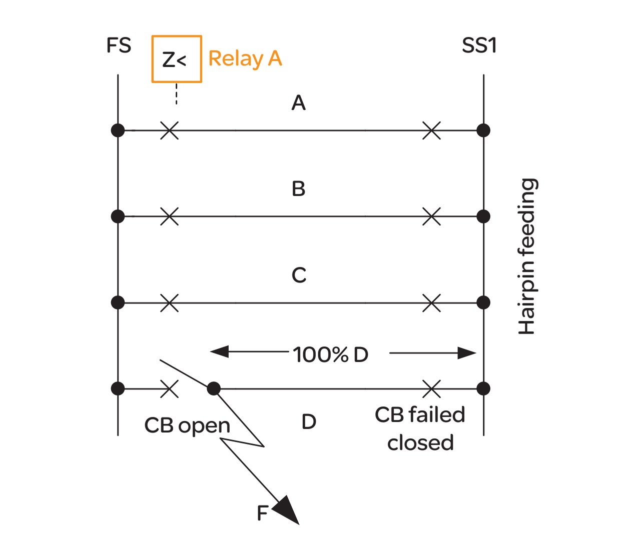

Figure C10.10:
Fault scenario for Zone 3 minimum reach (hairpin feeding)

D = impedance of longest hairpin fed section

A = impedance of protected section

R = impedance of sections B and C in parallel

Z = impedance of sections A, B, C, D in parallel

To avoid under-reaching for both normal feeding and hairpin fed faults, the higher of the two calculated impedances is used as the Zone 3 reach setting. Occasionally the Zone 3 reach requirement may be raised further, to offset the effects of trains with regenerative braking, which would provide an additional current infeed to the fault. An additional 5% reach increase would generally be sufficient to allow for regenerative under-reach.

3.3.4 Reverse reaching zones

An impedance measurement zone with reverse reach is typically applied to provide back-up protection for the local busbar at a paralleling/sectionalising substation. A typical reverse reach is 25% of the Zone 1 reach of the relay. Typically Zone 3 is set with a reverse offset to provide this protection and also so that the Zone 3 element will satisfy the requirement for Switch-on-to Fault (SOTF) protection.

3.3.5 Distance zone time delay settings

The Zone 1 time delay ($tZ1$) is generally set to zero, giving instantaneous operation.

The Zone 2 time delay ($tZ2$) should be set to co-ordinate with Zone 1 fault clearance time for downstream catenaries.

The total fault clearance time will consist of the downstream Zone 1 operating time plus the associated breaker operating time. Allowance must also be made for the Zone 2 elements to reset following clearance of an adjacent line fault and also for a safety margin. A typical minimum Zone 2 time delay is of the order of 150-200ms. This time may have to be adjusted where the relay is required to grade with other Zone 2 protection or slower forms of back-up protection for downstream circuits.

The Zone 3 time delay ($tZ3$) is typically set with the same considerations made for the Zone 2 time delay, except that the delay needs to co-ordinate with the downstream Zone 2 fault clearance. A typical minimum Zone 3 operating time would be in the region of 400ms. Again, this may need to be modified to co-ordinate with slower forms of back-up protection for adjacent circuits.

3.4 Load avoidance

Figure C10.4 shows how the distance relay trip characteristics must avoid regions of the polar plot where the traction load may be present. This has historically been achieved by using shaped trip characteristics, such as the lenticular characteristic. Commencing around 1990, the benefits of applying quadrilateral characteristics were realised with the introduction of integrated circuit relays.

A quadrilateral characteristic permits the resistive reach to be set independently of the required forward zone reach, which determines the position of the top line of the quadrilateral element. The resistive reach setting is then set merely to avoid the traction load impedance by a safe margin and to provide acceptable resistive fault coverage. Figure C10.11 shows how the resistive reach settings are determined.

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3. Classical single-phase feeding

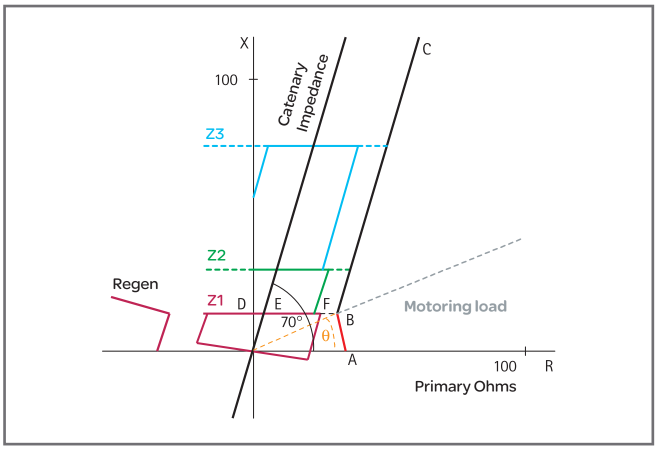

Figure C10.11:
Resistive reach settings for load avoidance

For all quadrilateral characteristics, impedance point B is the critical loading to avoid. The magnitude of the impedance is calculated from $Z=V/I$ taking the minimum operational catenary voltage and the maximum short-term catenary current. The catenary voltage is permitted to fall to 80% of nominal or less at the train location under normal operating conditions, and the short term current loading to rise to 160% of nominal – these worst-case measured values should be used when aiming to find the lowest load impedance.

The phase angle of point B with respect to the resistive axis is determined as:

$\theta = COS^{-1}$ (max lagging power factor)

The diagram shows how resistive reach E-F for Zone 1 has been chosen to avoid the worst-case loading by a suitable margin of 10%-20%. Zones 2 and 3 reach further, thus the effect of any angular errors introduced by CTs, VTs etc. will be more pronounced. It is therefore common to set the resistive reaches progressively marginally smaller for zones with longer reaches.

A practical setting constraint to ensure that zones with long reaches are not too narrow, and not overly affected by angle measurement tolerances, is for the resistive reach not to be less than 14% of the zone reach.

3.5 Enhanced modern relay characteristics

Figure C10.12 illustrates the polygonal distance relay characteristics of a modern numerical railway distance relay. Introduction of a γ setting modifies the basic quadrilateral characteristic into a polygonal one, in order to optimise fault impedance coverage and load avoidance for modern railway applications.

The use of the γ setting allows a load avoidance notch to be placed within the right-hand resistive reach line of the quadrilateral. γ is chosen to be around 10 degrees greater than the worst-case power factor load angle, limiting the resistive reach to R_g to avoid all load impedances. For impedance angles greater than γ, the zone resistive reach R applies, and the fault arc resistive coverage is improved. This is especially beneficial for Zone 3 back-up protection of adjacent catenaries, where the apparent level of arc resistance will be raised through the effect of parallel circuit infeeds at the intervening substation.

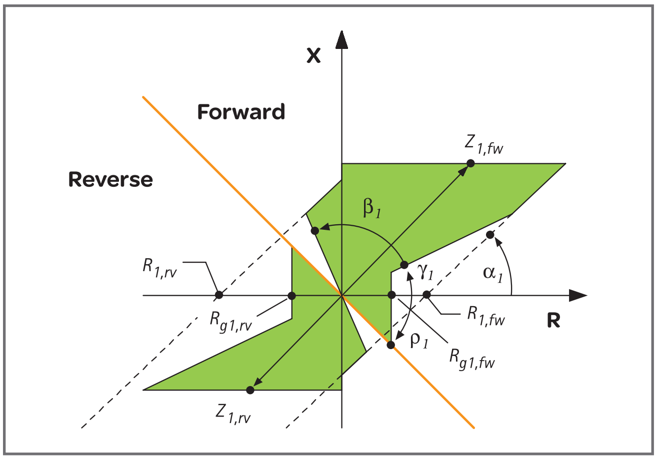

Figure C10.12:
Polygon distance characteristics

3.6 Impact of trains with regenerative braking

It is common for the Zone 1 characteristic to apply to the forward direction only. However, other zones may be set to have a reverse reach – see Section 3.3.4 for details. Another case where reverse- reaching zones may be required is where trains having regenerative braking are used.

Such trains usually regenerate at a leading power factor to avoid the creation of overvoltages on the catenary. Where a regenerating train contributes to fault current, the fault impedance measured by distance relays may shift up to 10° greater than α . Some railway administrations require that the fault impedance remains within the trip characteristic, and does not stray outside the top left hand resistive boundary of the polygon. This can be obtained by setting the reverse resistive reach (R_{rv}) to be greater than the forward resistive reach (R_{fw}).

3.7 Other relay characteristics

Recent relay technology developments also allow the use of detectors for rate of change of current and voltage (di/dt and dv/dt). These detectors are used to control the time delays associated with time-delayed Zones 2 and 3, and hence obtain better discrimination between load and fault impedances. The technique is still in its infancy, but shows significant potential for the future.

4. Catenary thermal protection

It is essential that railway catenaries remain in the correct position relative to the track, thus ensuring good current collection by train pantographs. The catenary is designed to operate continuously at a temperature corresponding to its full load rating, where heat generated is balanced with heat dissipated by radiation etc. Overtemperature conditions therefore occur when currents in excess of rating are allowed to flow for a period of time. Economic catenary design demands that the catenary rating be that of the maximum average continuous load expected. Peaks in loading due to peak-hour timetables, or trains starting or accelerating simultaneously are accommodated using the thermal capacity of the catenary - in much the same way as use is made of transformer overload capacity to cater for peak loading.

It can be shown that the temperatures during heating follow exponential time constants and a similar exponential decrease of temperature occurs during cooling. It is important that the catenary is not allowed to overheat, as this will lead to contact wire supporting arms moving beyond acceptable limits, and loss of the correct alignment with respect to the track. The period of time for which the catenary can be overloaded is therefore a function of thermal history of the catenary, degree of overload, and ambient temperature with cooling conditions.

The tension in the catenary is often maintained by balance weights, suspended at each end of tension lengths of contact wire. Overthermal temperature will cause the catenary to stretch, with the balance weights eventually touching the ground. Further heating will then result in a loss of contact wire tension, and excessive sagging of the contact wire. To provide protection against such conditions, catenary thermal protection is provided.

4.1 Catenary thermal protection method

Catenary thermal protection typically uses a current based thermal replica, using load current to model heating and cooling of the protected catenary. The element can be set with both alarm (warning) and trip stages.

The heat generated within the catenary is the resistive loss ($I^2R \times t$). Thus, the thermal time characteristic used in the relay is therefore based on current squared, integrated over time. The heating leads to a temperature rise above ambient temperature, so in order to calculate the actual catenary temperature, the relay must know the ambient temperature along its' length. This can be either set as an assumed 'default' ambient temperature, or measured, typically using a temperature probe mounted externally to the substation building. However, the tension length of a contact wire may be over 1km, and traverse cuttings and tunnels - with resulting significant changes in the local ambient temperature. Therefore, the probe should ideally be mounted in a location that most accurately models the coolant air around the catenary for the majority of the protected section:

a. if exposed to direct sunlight, then the probe should be mounted to face the sun

b. if shaded from sunlight, such as running in a tunnel, then the probe should be mounted on an exterior wall facing away from the sun

c. if running in a cutting, shielded from wind, the probe should be mounted in the lee of the substation

d. if exposed to the wind, the probe should also be mounted on an exposed wall

It is virtually impossible to site the probe such as to exactly model the ambient conditions along the protected section, and thus a typical error in the allowable temperature rise of between 1°C and 3°C will result (for well-sited and poorly-sited probes, respectively). RTD and CT errors, along with relay tolerances may also introduce further errors of up to 1°C in the thermal model. Overall, the error in the temperature reading above the 20°C rated ambient could be 4°C. Therefore, relays may have a setting to compensate for such measurement tolerances, to ensure that the trip will not occur too late to prevent mechanical damage. Some relays may have an option to express the above tolerance as a percentage of the temperature at which a trip is required, rather than in absolute terms.

5. Catenary backup protection

Railway systems often use overcurrent protection as time-delayed back-up protection for the main distance protection. Two different philosophies for overcurrent protection are typical:

a. definite-time overcurrent protection (DTOC)

b. back-up overcurrent protection (BUOC)

5.1 Definite-time overcurrent protection (DTOC)

This form of protection is continually in service, in parallel to the distance relay elements, either included within the same relay as the distance function, or as a separate relay. The latter approach is currently more common for installations at Feeder Stations. This is due to the perceived increase in security and reliability obtained from the redundancy of separate devices. However, the trends evident in other protection applications to provide more functionality within a single relay will in time surely apply to this area as well.

It operates on the basis of conventional definite-time overcurrent protection, as described in Chapter [C1: Overcurrent Protection for Phase and Earth Faults]. The time settings are chosen to ensure that the distance relay elements should operate first, thus the overcurrent elements only operate if the distance elements fail, or if they are out of service for some reason.

5.2 Back-up overcurrent protection (BUOC)

This form of back-up protection is switched in service only during periods when the distance protection is out of service. A typical example is where VT supervision or a measuring circuit monitoring function detects a blown VT fuse or an MCB trip. In such instances the distance protection is automatically blocked, and the BUOC elements are automatically brought into service, such that catenary protection is not lost.

Methods of setting overcurrent protection are covered in Chapter [C1: Overcurrent Protection for Phase and Earth Faults]. An example of using overcurrent protection is given in Section 8.

6. Auto-transformer feeding

High-speed rail lines, with maximum speeds in excess of 200km/h (125mph) have much higher traction power demands. This is not only to cope with the peak power required for rapid acceleration to high speed, but also to cope with the steeper gradients that are commonly encountered along such routes. The total traction power per train may amount to 12-16MW, comprising two or more power cars per unit and often two units coupled together to form a complete train. The heavy load currents drawn may cause significant voltage drops across the catenary feeding impedance with a classical feeding arrangement – depending on the section length being fed and the traffic frequency (in both directions). To avoid a decrease in train performance, feeder stations and parallelling substations for classical systems would have to be sited at prohibitively short intervals. In such circumstances, especially where the route involves new construction, auto-transformer feeding is normally favoured.

6.1 Description of auto-transformer feeding

Auto-transformer feeding uses a high voltage system comprising of a centre-tapped supply transformer, catenary wire and a feeder wire. The feeder wire is aerially mounted on insulators along the back of the overhead line masts. The running rails are connected to the centre tap of the supply transformer, and hence a train sees only half of the system voltage. Auto-transformers located at intervals along the tracks ensure division of load current between catenary and feeder wires that minimises the voltage drop between the supply transformer and the train. Figure C10.13 shows auto-transformer feeding for the typical 25-0-25kV system found in Western Europe.

The use of auto-transformers (AT) results in distribution losses that are lower than for classical 25kV feeding, and therefore can support the use of high power 25kV traction units. Feeder substation spacing can also be much greater than if a classical feeding system is used. Fewer substations means less maintenance and reduced operating costs. Two-pole switchgear is normally used to isolate both the feeder and catenary wires in the event of a fault on either wire.

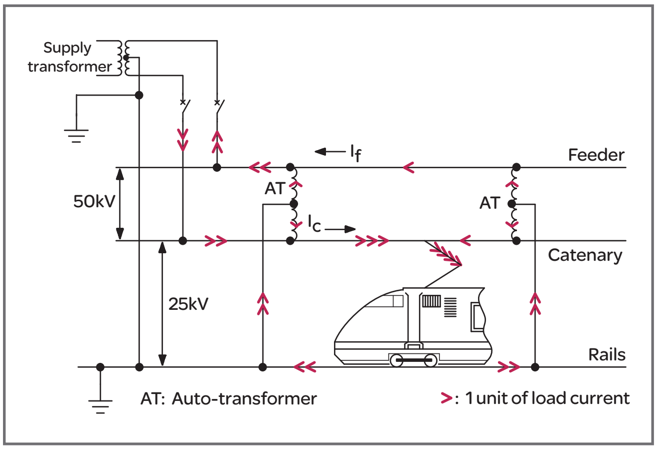

Figure C10.13:
25-0-25kV auto-transformer feeding

6. Auto-transformer feeding

However, some auto-transformer systems allow single wire tripping, where separate distance protection is provided for each wire. The protection would then monitor the two 'halves' of the system independently, with Protection Zones 1 and 2 typically set to 85% and 120% of the protected impedance - similar to the protection of a classical catenary system. Figure C10.13 also illustrates the distribution of load current for a train situated midway between AT locations.

The topology of the AT system is often similar to the classical system shown in Figure C10.4, except that the grid supply transformer 50kV secondary winding is wound as a centre-tapped AT winding, and ATs are connected catenary-rail-feeder at each downstream substation and at intervening locations.

Figure C10.14 shows a typical protection one-line diagram for an auto-transformer-fed system, while Figure C10.15 shows the construction of the catenary system.

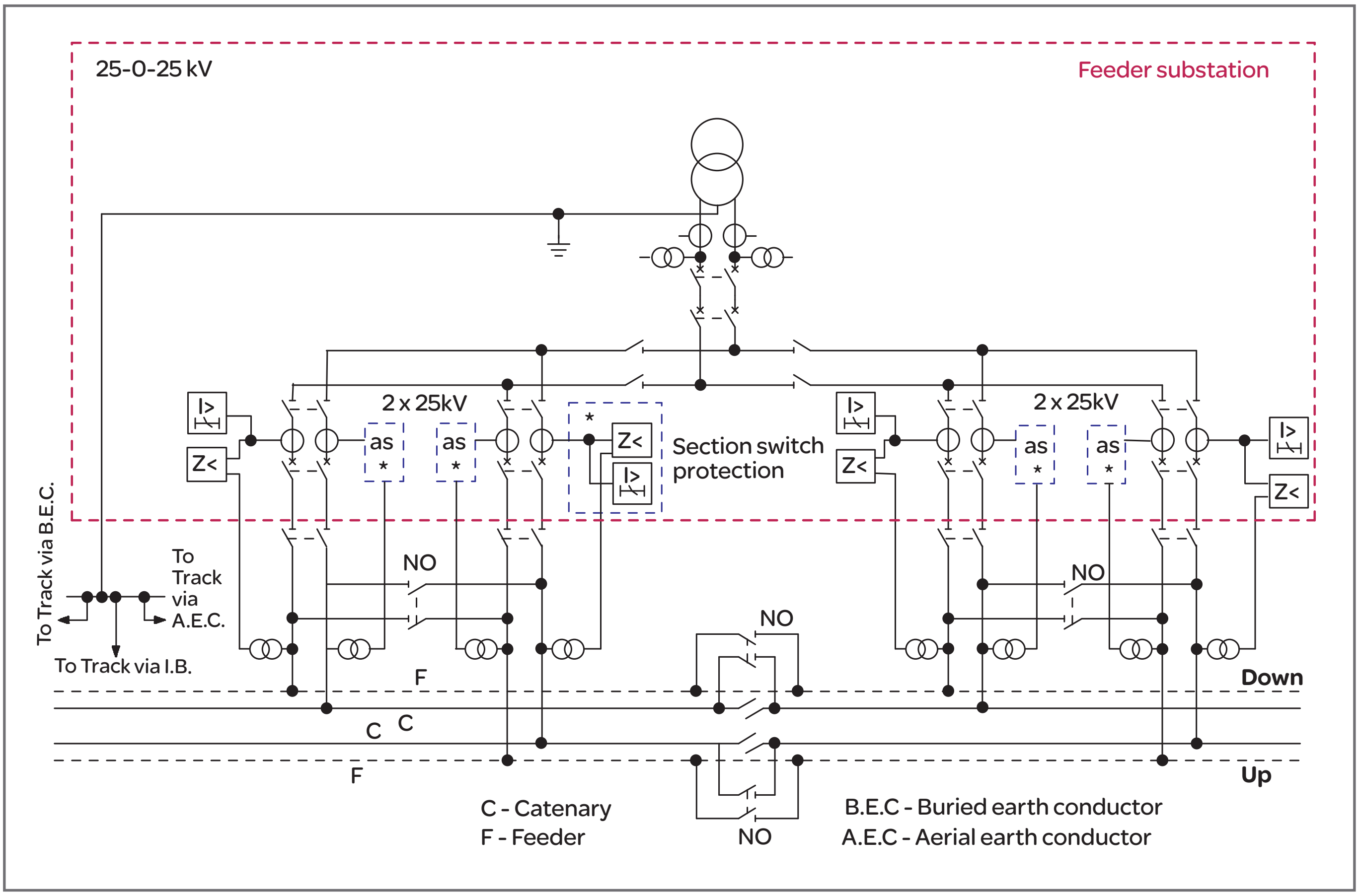

Figure C10.14:
Auto-transformer-fed system one-line diagram showing protection

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6. Auto-transformer feeding

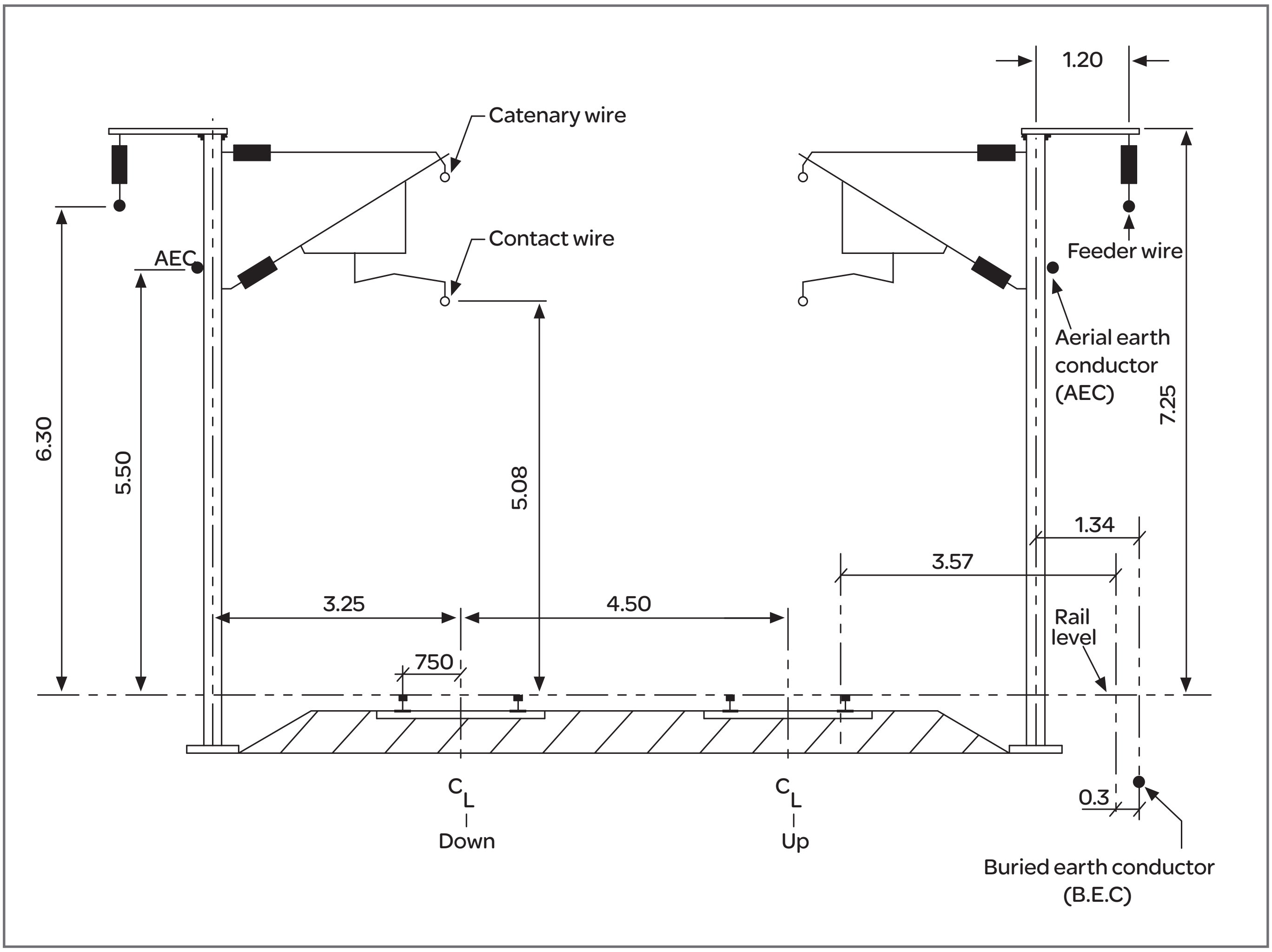

Figure C10.15:
Typical auto-transformer–fed catenary layout

6.2 Auto-transformer system protection philosophy

From Figure C10.13 it can be seen that the summation $(I_e - I_f)$ at any location will be equal to the downstream traction load current. The same is true for fault current, and so physically performing this current summation, through the parallel connection of feeder and catenary CT secondary windings, or mathematically summating within a protection relay, can be the basis for auto-transformer circuit protection.

To discriminate between normal load current and feeder wire or catenary faults, distance protection is commonly applied, with $(I_c - I_f)$ being the measured current. The measured voltage is generally the catenary to rail voltage. The relatively low reactance of the ATs – typically 1% on a 10MVA base – ensures that any fault voltage drop on the catenary will be proportional to the feeder wire voltage drop.

When applying zones of distance protection to AT systems, with double-pole tripping, it should be appreciated that it is not usually possible to provide fully discriminative protection. When the catenary and feeder currents are combined, the relationship between impedance and distance-to-fault is non-linear.

Consequently, it is more difficult to set Zone 1 to be under-reaching and Zone 2 to be overreaching in the normal manner. The approach that is normally adopted is to set the Feeder Station distance protection to detect all faults along any track, up to, but not beyond, the Mid-Point Substation. It can be arranged that operation of any distance relay will trip all Feeder Station breakers. In the event of any fault up to the $MPSS$, simultaneous tripping of all the track feeder circuit breakers at the FS will cut supplies to all tracks. Where this scheme is adopted, the application of auto-reclosing is essential to restore supplies to all but the permanently faulted section of catenary and feeder. The momentum of moving trains will ensure that little speed is lost during the dead time of the auto-reclose sequences. Considerations relating to the application of auto-reclosure are detailed in Section 5.5. With high speed lines generally being better fenced, and having fewer overbridges and greater electrical clearances compared to classical systems, the infrequent losses of supply cause few operational problems. As tripping of circuit breakers at the FS isolates all line faults, there is then no need to have switchgear at downstream substations rated to interrupt fault current. For economy, load-breaking switches are used instead of breakers at $SS1$ and $SS2$ in Figure C10.4.

6.3 Distance protection zone reaches

Figure C10.16 illustrates the typical locus of impedance measured at the FS, for a catenary-to-earth fault, at a variable location upstream of $SS2$, for any one track.

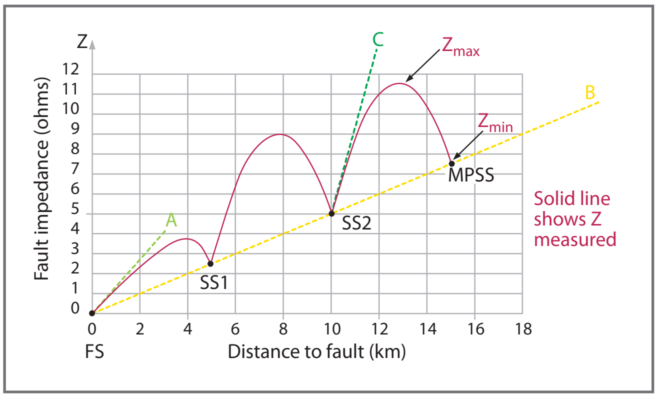

Figure C10.16:
Variation of impedance measurement with fault location along track

While a similar effect exists for classically-fed systems, it is small by comparison and normally ignored. The impedance measured is defined as:

$$Z = \frac{V_{catenary}}{\left(I_{catenary} - I_{feeder}\right)}$$

For clarity, only the impedances measured for a catenary-to-earth fault located upstream of $SS2$ are plotted. The hump-like impedance locus in Figure C10.16 has a number of identifiable trends:

a. the initial slope of the locus, in Ω/km, shown as line 'A'. This is according to the catenary-to-rail loop impedance (the 25kV loop in Figure C10.13), since the fault current flows almost entirely in the catenary-rail loop for faults close to a feeding point

b. at AT locations, slope 'B' shows how the effective ohms/km trend is less than half the catenary-to-feeder loop impedance (the 50kV loop in Figure C10.13) due to the method of impedance measurement and due to the fault current distribution. For a catenary-earth fault located at an auto-transformer, the fault current will circulate almost entirely in the catenary-feeder loop rather than in the catenary-rail loop. Additionally, the impedance of the catenary-feeder loop is lower than that of the catenary-rail loop, as the feeder cable is a better conductor than the rails

c. beyond $SS1$, the effect of parallel feeding from other circuits between the FS and $SS1$ means that slope 'B' for a single circuit beyond $SS1$ is greater than slope 'A'. With reference to Figure C10.7, the system simulated is four track, thus the gradient of 'C' will be approximately four times that of 'A' (marginally higher than four for the inner tracks, and less than four for outer tracks)

Considerations for the setting of distance relay reaches are detailed in the following sections.

6.3.1 Zone 1

The Zone 1 elements of any FS distance relay should not overreach and trip for faults beyond the $MPSS$, when the mid-point bus section breaker is closed. If it is known that the $MPSS$ is definitely open, then there is no real reach constraint for distance protection. However, if the mid-point breaker is closed, or no status information is communicated to the protection to control overreach, through reversion to an alternative setting group, then the relay must not trip for the lowest impedance for a fault at the $MPSS$ busbar. Referring to Figure C10.16, this fault impedance would be Z_{min} along slope B (to 15km and 7.5 Ω). The applied Zone 1 setting should be restricted to 85% of this impedance, to allow for all measurement and impedance data tolerances.

A lower reach setting might be necessary to prevent unwanted tripping with aggregate magnetising inrush currents following circuit energisation. This will depend on the response of the relay elements to inrush current and to the number of ATs applied. For relays that have magnetising inrush restraint or some means of providing immunity or reduced sensitivity to inrush currents such a constraint may not apply.

6.3.2 Zone 2

Allowing for under-reaching errors, the Zone 2 reach ($Z2$) should be set in excess of 115% of the protected line impedance for all fault conditions. The relevant impedance in Figure C10.16 would be the Z_{max} peak between $SS2$ and $MPSS$. A typical value of Z_{max} would be approximately 11.5 Ω at 13km distance from the feeder station.

If trains with regenerative braking are in service along the protected track a 20% additional reach margin would typically be applied.

With the stated Zone 1 and Zone 2 setting policy, relays at the Feeder Station provide complete track protection up to the $MPSS$.

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6. Auto-transformer feeding

6.3.3 Zone 3

Zone 3 may be applied to provide remote back-up protection for faults beyond the $MPSS$, or with a longer reach to cover instances where ATs are switched out of service, such that the effective normal feeding impedance becomes higher.

6.4 Distance zone time delay settings and load avoidance

The principles used are identical to those for classical feeding, with one exception. A short time delay of the order of 50ms may be used with the Zone 1 element if a relay without magnetising inrush restraint is used.

The relay uses (I_e-I_f), which is measuring the combined load current of all trains at their pantographs. Therefore, the load impedance to avoid is that measured from catenary to rail (the '25kV' impedance in Figure C10.11).

6.5 Implications of using two-pole switching and auto-reclosure

A full discussion of operational implications is beyond the scope of this chapter, thus only the important points are listed:

a. it is usual to remove all parallelling between tracks prior to any breaker reclosing. This avoids repetitive re-tripping of healthy catenary sections as multiple track feeder circuit breakers are being reclosed after clearance of a fault on one feeder. Paralleling is removed by opening the motorised isolators at all SS and $MPSS$ locations. Following feeder breaker reclosure, the tracks will be radially fed. A persistent fault would only result in re-tripping of the faulted track circuit breakers

b. in the period where tracks are being radially-fed, the relays at the FS should only trip their own track circuit breakers. Cross-tripping of parallel track circuit breakers should be inhibited

c. protection at the FS can trip for an AT fault. Since there would typically be no circuit breakers at the SS and $MPSS$ auto-transformer locations, AT protection should wait for loss of line voltage during the dead time of FS circuit breakers before initiating the opening of a local motorised disconnector switch. This action should take place within the dead time so that the faulted AT will have been disconnected before reclosure of the FS breakers

d. with radially fed tracks, multiple shot auto-reclosing is often applied to dislodge any debris (wildlife or other stray material) that may have caused a semi-permanent fault. Before the last auto-reclose shot, it is common to disconnect all ATs downstream of the FS. With all ATs and paralleling removed the faulted circuit distance relays would then see a linear relationship between the impedance measured and the distance to fault. The results obtained from conventional, integral fault location algorithms would then offer rectification crews a fairly accurate estimate of where the permanent fault might be located

e. it may be necessary to automatically increase the Zone reaches of distance relay elements before the final auto-reclose attempt to allow for the higher catenary-to-rail fault loop impedance up to the $MPSS$ rather than the lower catenary-feeder loop impedance. This may be achieved by switching to an alternative setting group with $Z2$ set higher than previously

6.6 Backup protection

Backup protection considerations for auto-transformer fed systems are similar, in principle, to those for classical systems, as described in Section 5.

7. Feeder substation protection

Each feeder substation comprises transformers, busbars, cables, switchgear, etc. All of these items require protection. Due to the much higher frequency of faults on the catenary system, special attention must be given to ensuring that the substation protection remains stable for catenary faults, whilst offering dependable protection for substation faults.

Other than this, there are no special requirements for the protection of feeder substation equipment and the forms of protection detailed in Chapters [C1: Overcurrent Protection for Phase and Earth Faults] and [C7: Transformer and Transformer-Feeder Protection] are directly applicable, on a single phase basis.

8. Delta function

A significant new protection feature is the Delta function for 1 AC and 2 AC contact line systems which is intended to detect high resistance earth faults with minimal time delay. As a basis an expanded harmonic supervision algorithm is required, monitoring the 3rd and 5th harmonics.

AC traction load conditions are distinctly different to industrial medium-voltage applications. Due to the structure of contact lines, the traffic situation and environment, a rapid and frequent variation in load and the occasional overload condition must be taken into account. In addition to the varying load conditions, fault scenarios must also be accurately detected. While the magnitude of fault current may vary from 40 % to 100 % of the short circuit capacity, the frequency of fault inception coupled with the high tension in the contact wire makes fast fault clearance the ultimate requirement for the protection device.

At times the short-circuit scenarios may not be fulfilled, especially in the case of high impedance faults caused by wildlife, vegetation or bond open earth faults causing low return current. The resultant fault current magnitudes can be similar to expected operating loads in such cases. In these circumstances, distance protection devices have difficulty detecting such faults.

Modern electrified locomotives for heavy load and high-speed passenger trains are provided with three-phase technologies for the traction motors which make use of static converters for onboard drives. This energy conversion produces a significant proportion of harmonics, particularly odd numbered harmonics. Typical percentage levels of harmonics, evaluated in 50 Hz contact lines, are provided in Table C10.2.

Harmonics	Frequency	Percentage
Third harmonics	150 Hz	~ 20%
Fifth harmonics	250 Hz	~ 10 %
Others	-	~ 8 %

Table C10.2:
Mean harmonic content, generated by engines

As indicated, the majority of the rolling stock loads introduce significant third or fifth harmonic levels into the AC power system, generated by the locomotive converters. AC traction systems experience inrush current when inductive loads such as auto-transformers or track switch heating or the electrical rolling stock themselves are energised. These inrush currents, high in second harmonic components, are also present when electric locomotives pass through neutral sections.

Load currents in contact lines are characterised by a substantial amount of measurable harmonic content. In contrast, short circuit fault currents are mostly sine wave current at fundamental frequency and contain little harmonic content. Harmonic levels are an important characteristic of the current profile that can be utilised to distinguish between load and fault conditions.

Detection of high impedance faults is based on the fact that fast current changes, or jumps, without a significant harmonic content, e. g third harmonic, are indicative of fault conditions. This fact is well known and has been used in protection applications for many years.

For fault detection, the following elements must be securely fulfilled:

a. Minimum base current available

b. Current jump ΔI detected

c. No inrush blocking

d. Harmonic supervision of third harmonic not started

Supervision of the third harmonic level can be used for both blocking and stabilisation functionality. When the stabilisation function is activated, a multiplying factor is used to dynamically increase the current jump threshold if harmonics due to load are detected in the system.

The application may be viewed graphically as shown in Figure C10.17.

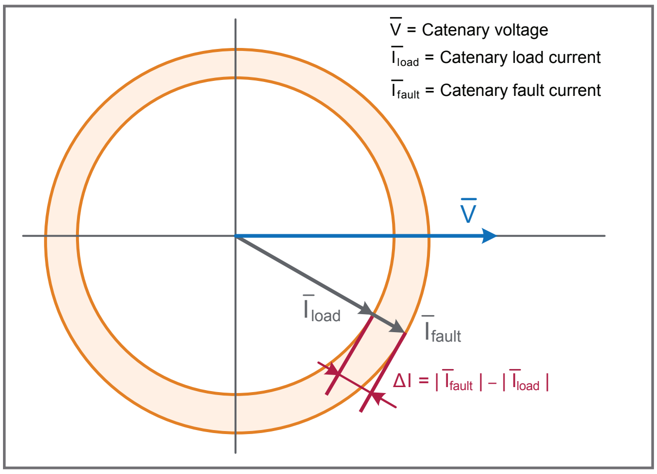

Figure C10.17:
Basic function ΔI

A fault condition is detected by a current jump ΔI when a minimum current level is exceeded at the same time. Inrush conditions, due to second harmonic detection, will block the complete function during the inrush event. Depending on the operating mode for the harmonic supervision, the ΔI criteria will be blocked or stabilised with a detected high third harmonic content.

8. Delta function

In addition to the elements described for the basic application, enhanced applications make use of one or more additional elements to provide added reliability and enhanced discrimination between load and fault conditions.

The following additional elements must be fulfilled securely, if enabled:

a. Current angle change $\Delta\varphi$ detected

b. Reactance supervision criteria

c. Enhanced harmonic supervision of third and fifth harmonic not started

d. No functional blocking by the auxiliary contact of the circuit breaker

The current angle change and reactance supervision elements make use of voltage signals to provide added stability and discrimination. A minimum angle change criteria ensures the current change is due to the onset of a fault, rather than load, while reactance supervision may be enabled to restrict the zone of operation to the immediate line section and avoid the need to time grade with downstream devices. Should failure of the voltage transformer circuits occur, the function can revert to the basic application or it may be blocked, if stability is no longer maintained.

Harmonic supervision may be expanded to include the fifth harmonic as well. This allows further flexibility to provide expanded stabilisation for the use of lower harmonic values for fault discrimination.

The application may be viewed graphically as shown in Figure C10.18.

A fault condition is detected by a ΔI value, stabilised by a current angle change $\Delta\varphi$, when a minimum current level is exceeded at the same time. Depending on the operating mode for harmonic supervision the ΔI criteria will be blocked or stabilised with a detected high third or fifth harmonic component. The inrush detection function works as described in the basic application.

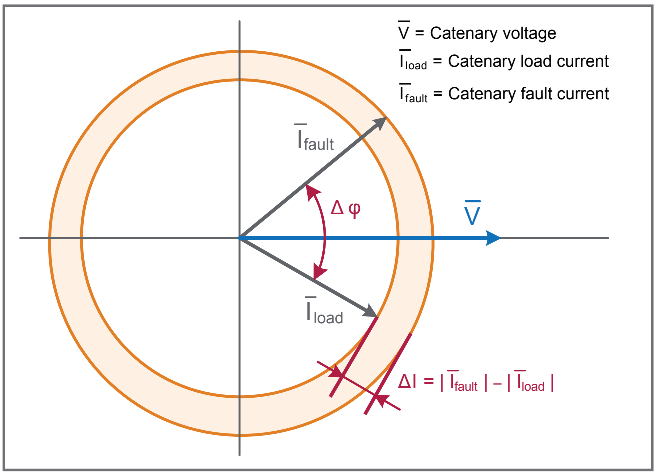

Figure C10.18:
Basic function ΔI with additional stabilisation $\Delta\varphi$

The implementation for high impedance fault detection performs a significant additional function in the protection of a.c. railway contact lines for many rail network operators. In addition to the main distance and backup over-current protection devices, a third device for high impedance fault detection was used in the past in many countries. By integrating all three protection elements and combining this with additional automation, supervision and self-monitoring, a modern multifunctional railway protection device with comprehensive functionality provides a cost-optimised solution for all a.c. railway contact line installations.

9. Example of classical system protection

Figure C10.19 depicts a typical 25kV system, where the settings for the relay protecting track feeder *TF-1* at Substation *S1* are to be calculated. The inputs to the relay are derived from the track feeder CT adjacent to the circuit breaker, and from a section busbar VT at busbar *S1* (a catenary-side VT would be equally suitable). The system data is given in Table C10.3. A MiCOM P438 relay is used in the example.

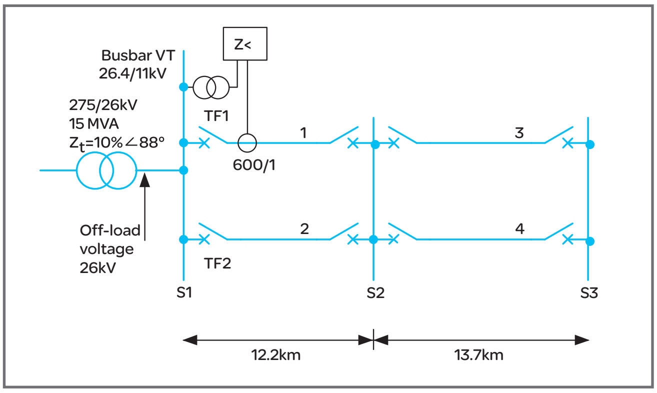

Figure C10.19:
Network diagram – Example calculation

Catenary thermal protection	Data
Catenary impedance	0.26 + j0.68 Ω/km
Booster transformer impedance	0.051 + j0.21 Ω
Booster transformer spacing	Every 3km
Maximum load current	900A
CB type	Vacuum
CB trip time	0.065 s
Max zone 1 protection trip time	0.045 s
Catenary design temperature range for correct tension	-18°C to 38°C
Typical assumed max. winter temperature (610A rating)	10°C
Typical assumed max. spring/autumn temperature (540A rating)	20°C
Typical assumed summer temperature (515A rating)	23°C
Worst-case assumed hottest ambient	28°C
Temperature for balance weights to touch ground	38°C
Temperature at which 20% loss of tension, train speeds must be restricted	48°C
Temperature at which possible damage due to clashing of supports at overlaps occurs	56°C
Heating time constant - daytime	5 mins
Cooling time constant - nighttime	7 mins

Table C10.3:
Electrified railway system data

9.1 Section impedance data

The first step is to calculate the primary impedance for the catenary sections to be protected. Zone 1 for the relay associated with feeder *TF-1* protects section 1, however the backup protection offered by Zones 2 and 3 must discriminate with downstream relays and so the impedance of sections 2, 3 and 4 needs to be calculated too. In this example each pair of catenaries runs between the common substations, and so the impedance of adjacent sections will be identical. There are situations where this is not the case, of which:

a. the sections to be protected consist of four tracks

b. the two tracks follow different routes due to the geography of the route and hence may not be of the same length

c. if there is a junction within a section

are three examples.

The equivalent section impedance per kilometer is given by the formula:

$$Z_{sect} / \text{km} = \text{line impedance / km} + \left(\frac{BT\ impedance}{BT\ spacing} \right)$$

$$(0.26 + j0.68) + \left(\frac{(0.051 + j0.21)}{3} \right)$$

$$= 0.277 + j0.75\Omega/\ km$$

$$= 0.8\angle\ 69.7°\Omega/\ km$$

This will be rounded up to 70° as the nearest settable value of the common characteristic line angle of the relay, α.

Distance protection relays are often set and injection-tested in terms of the impedance on the secondary side of the CTs/VTs used. Therefore, it is helpful for testing if the primary impedances on the system are converted to secondary quantities. The equation to be used is:

$$Z'_{sect} = Z_{sect} \times \frac{CT\ ratio}{VT\ ratio}$$

where:

Z_{sect} = system impedance referred to primary

Z'_{sect} = system impedance referred to secondary

Hence,

$$Z'_{sect} = Z_{sect} \times \frac{600/1}{26400/110}$$

$$= Z_{sect} \times 2.5$$

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9. Example of classical system protection

9.2 Section impedance calculations

The section impedances can be calculated as follows:

9.2.1 Sections 1 and 2

The impedances for sections 1 and 2 are:

$Z_{sect} = 12.2 \times 0.8 = 9.76\Omega$

$Z'_{sect} = 9.76 \times 2.5 = 24.4\Omega$

9.2.2 Sections 3 and 4

The impedances for sections 3 and 4 are:

$Z_{sect} = 13.7 \times 0.8 = 10.96\Omega$

$Z'_{sect} = 10.96 \times 2.5 = 27.4\Omega$

9.3 Zone 1 reach calculation for TF-1

The Zone 1 forward reach is set to be 85% of the section 1 impedance, referred to the secondary of the relay.

Hence, the forward reach is calculated as

$Z1_{fw} = 24.4 \times 0.85 = 20.75\Omega$

Zone 1 is not required to operate in the reverse direction, so the setting $Z1_{rv}$ is set to blocked.

9.4 Zone 2 reach calculation for TF-1

Two configurations have to be considered in the setting of the Zone 2 reach. These are:

a. the 'follow-on' configuration of Figure C10.7

b. the 'Hairpin' feeding configuration of Figure C10.8.

The setting required is the lowest of the above two configurations.

9.4.1 'Follow-on' configuration

Figure C10.7 shows the condition to consider, with two track feeding only for the area fed by Substation $S1$. Equation C10.1 is used to calculate the reach:

$$Z2 = \frac{\left((Z + 0.7E) \times \frac{(A + R)}{R} \right)}{1.15}$$

where:

Z = impedance of sections 1 and 2 in parallel

A = the track section of interest, section 1

R = parallel fault current path (section 2)

E = shortest following section (3 or 4)

Hence,

$$Z2 = (12.2 + 0.7 \times 27.4) \times \frac{\left(\frac{24.4 + 24.4}{24.4} \right)}{1.15}$$

$$= (12.2 + 0.7 \times 27.4) \times \frac{2}{1.15}$$

$$= 54.6\Omega$$

Notice how for two track feeding, $(A+R)/R$ above becomes 2, due to a fault current split between two identical parallel paths.

9.4.2 'Hairpin' feeding configuration

Referring to Figure C10.8, it is apparent that with only two tracks, inner tracks B and C are not present. Once circuit breaker $TF\text{-}2$ at substation $S1$ is open, the impedance to the fault is merely 170% times the impedance of track section 1 or 2.

Thus, from Equation C10.2:

$$Z2 = \left(24.4 + \frac{(0.7 \times 24.4)}{1.15} \right)$$

$$= 36.1\Omega$$

For Zone 2 it is always the lower of the two calculated results that is used.

Therefore, use a setting of:

Forward reach $Z2_{fw} = 36.1\Omega$

The Reverse reach, $Z2_{rv}$, is set to blocked, as only forward directional operation is required.

9.5 Zone 3 reach calculation for TF-1

In similar fashion to the Zone 2 reach, the 'follow-on' and 'Hairpin' fault configurations have to be considered. As Zone 3 must tend to overreach rather than underreach, 120% of the fault impedance calculated is used as the setting and the higher of the two possible settings is used.

9.5.1 'Follow-on' fault configuration

Figure C10.9 shows the configuration for a follow-on fault with two tracks: It is apparent that the calculation is exactly as for Zone 2 follow-on, except that the multiplier of 0.7 (70%) is replaced by 1 (100%).

$Z3 = (12.2 + 27.4) \times 2 \times 1.2 = 95.1\Omega$

9.5.2 'Hairpin feeding' fault configuration

Repeating the same for hairpin feeding (Figure C10.10, Equation C10.4):

$Z3 = (24.4 + 24.4) \times 1.2 = 58.6\Omega$

Hence, use a setting of:

Forward reach $Z3_{fw} = 95.1\Omega$

For Zone 3, a reverse reach is required to act a backup to the upstream protection. The usual setting is 25% of the Zone 1 forward reach.

Therefore, use a setting of: Reverse reach

$Z3_{rv} = 0.25 \times 20.75 = 5.2\Omega$

9.6 Zone time delays

The Zone 1 time delay will be set to instantaneous operation ($t1 = 0$) – it is not common practice to time-grade this zone with the primary protection fitted on board the trains.

Zone 2 ($t2$) should be delayed as follows:

$t2 = CB\ max\ trip\ time + Relay\ max\ trip\ time + 50ms\ margin$

Hence,

$t2 = 65 + 45 + 50 = 160ms$

As all of the protection and circuit breakers are identical, this value can be used for $t2$. If the downstream relays were electromechanical (typically 40-70ms slower than numerical), or the circuit breakers were oil insulated (OCBs, typically 40 to 60ms slower than VCBs), then the $t2$ delay would need to be extended accordingly. The 50ms margin allows for the reset time of the $Z2$ element.

The Zone 3 time delay can typically be set double the minimum calculated above.

However, as Zone 3 is often most at risk of unwanted pickup due to train starting currents or momentary overloads, a longer setting of $t3 = 500ms$ is applied.

9.7 Overcurrent protection

Overcurrent protection can be applied to the 25kV system in Figure C10.19. For railway applications, non-directional overcurrent protection is normal. The simplest application is for track feeders at Feeder Stations, such as $TF\text{-}1$. At this location and with normal feeding, any fault current will naturally be flowing away from the busbar, and so no reverse operation can occur. At downstream substations it will not be possible to apply overcurrent protection in a similar way, and any elements enabled would tend to be set with long time delays to ensure that all of the distance protection zones are given sufficient time to trip beforehand.

9.7.1 Back-up overcurrent (BUOC) at feeder stations

Should the distance protection be out of service, two BUOC overcurrent elements could be set. Firstly a high set overcurrent element is set to underreach the protected section, mimicking Zone 1 operation. This can be set for instantaneous tripping. Secondly, a lower-set overcurrent element can be applied to complete protection for the $TB\text{-}1$ section, to overreach the end of the protected section at $S2$. The overcurrent element of the relay would be set accordingly and with a definite time delay.

9.7.2 Calculation of fault current

In order to determine the overcurrent settings, the fault current measured by $TF\text{-}1$ CT for a fault adjacent to the $S2$ busbar needs to be calculated. There are two possible configurations to consider:

a. fault current for a fault at the end of section 1, with two tracks in-service

b. current for a fault at the end of section 1, with section 2 isolated for maintenance

For the first configuration, the fault current per track can be calculated as

$$I_{f1} = \frac{E}{2+\left(Z_t+Z_{sp}\right)}$$

where:

E = source voltage = $26.4kV$

Z_t = transformer impedance = $4.5 \angle 88°\Omega$

Z_{sp} = parallel impedance of sections 1 and 2

= $9.76 \angle 70°\Omega/ 2$

Note that the fault current splits into two parallel paths, fed via $TF\text{-}1$ and $TF\text{-}2$. Hence, the division by 2 in the equation for calculating the per-track current measured by the protection.

Hence,

$I_{f1} = 1.4kA$

For the second configuration,

$$I_{f2} = \frac{E}{\left(Z_t+Z_{s1}\right)}$$

where:

Z_{s1} = impedance of section 1

Hence,

$I_{f2} = 1.84kA$

9.7.3 Overcurrent setting for BUOC instantaneous stage

To prevent overreach, set at least 20% above the higher of the two fault scenarios:

$I_{inst} = 1840 \times 1.2 = 2200A$

The secondary current setting on the relay is found by dividing by the CT ratio:

$$I'_{inst} = \frac{2200}{600} = 3.68A$$

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9.7.4 Overcurrent setting for BUOC definite-time delayed stage

To ensure complete cover for short circuits in the protected section, the setting should be no greater than 80% of the lower of the two fault scenarios:

$$I_{oc} \leq 1400 \times 0.8 = 1100A$$

In terms of secondary quantities,

$$I_{oc} \leq 1400 \times 0.8 = 1100A$$

$$I'_{oc} = \frac{1100}{600} = 1.86A$$

A time setting no less than the Zone 2 distance time delay would be used, so tI'_{oc} = 250ms is suitable.

All overcurrent protection must have a pickup in excess of the maximum expected load current. Assuming that the maximum overloading would never exceed 150% of CT rating, the I'_{inst} and I'_{oc} settings are acceptable.

9.7.5 Definite time overcurrent (DTOC)

It is not general practice to set instantaneous protection elements that are running in parallel to the distance zones. Thus often just one definite time delayed stage is used. This setting can be applied at all locations, and must be in excess of the maximum load and overload current expected.

$$I_{dtinst} \geq 1.5 \times I_{flc}$$

where:

I_{flc} = full load current of feeder

Hence,

$$I_{dtinst} = 1.5 \times 600 = 900A$$

Referred to the secondary side of the CT,

$$I'_{dtinst} = \frac{900}{600} = 1.5A$$

The time delay applied must be longer than the $t3$ distance zone delay, so tI'_{dtinst} would be acceptable.

9.8 Thermal protection

The thermal data for the catenary are also given in Table C10.3. The calculation of the thermal protection settings is given in the following sections.

9.8.1 Thermal reference current/ temperature

The P438 requires a thermal rated current or reference current, I_{ref}, to be set that corresponds to full load current. The ambient temperature at which this applies qualifies this rated current. The reference current referred to the CT primary is given in Table C10.3 as:

$$I_{refp} = 540A$$

The relay setting is in terms of the secondary current. Hence, the secondary current setting on the relay is found by dividing by the CT ratio:

$$I'_{refs} = \frac{540}{600} = 0.9A$$

The ambient temperature t_{amb} at which I_{refp} occurs is set at 20°C.

9.8.2 Mechanical damage protection

The catenary temperature at which mechanical damage may begin to occur is 56°C. This must correspond to the MiCOM P438 thermal trip command, and so:

$$t_{catmax} = 56°C$$

Account must be taken of the measurement errors described in Section 4.1. The MiCOM P438 relay setting, θ_{trip}, must allow for these errors, which are taken to be 4°C. Hence,

$$\theta_{trip} = (56 - 4)°C = 52°C$$

To avoid chattering of contacts when the load current is close to the trip threshold, a hysteresis setting is provided on reset. Typically the hysteresis is set to 2%, such that following a trip, the thermal model must cool by 2% before the trip contacts will reset.

9.8.3 Dewirement protection

An alarm should be issued to warn the rail operator when speed restrictions are necessary, to avoid the risk of dewirements. From Table C10.3, the catenary temperature at which there is a danger of dewirement is 48°C. The same measurement errors apply as for the trip setting. Hence the relay setting, $\theta_{warning}$, is:

$$\theta_{warning} = (48 - 4) = 44°C$$

9.8.4 Maximum ambient temperature

It is possible to place a limit on the maximum ambient temperature that will be used by the thermal model, to avoid over-restrictive loading constraints being imposed.

From Table C10.3:

$$t_{ambmax} = 28°C$$

9.8.5 Default ambient temperature

If ambient temperature compensation is not being used, an assumed default coolant temperature ambient must be chosen. The default ambient temperature must be chosen to be sufficiently high to minimise the danger of undetected problems occurring on hot days, when the ambient temperature is well in excess of the default value. Similarly, it must not be so high that alarms and/or trips occur unnecessarily. A default ambient temperature (t_{ambdef}) of 20°C, would provide adequate protection, except for a calculated risk on certain hot summer days. Note that the rated thermal current at this ambient is I_{refs}.

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9.8.6 Thermal time constants

The catenary thermal model requires heating and cooling time constants to be specified. For most catenaries, the heating and cooling time constants would be expected to be equal. However, this may not always be the case, for example the cooling time constant at night may be longer than that applicable during the day. The relay can accommodate different settings where required. Conservative settings that assume the worst case time constants for heating (τ_h) and cooling (τ_c) would be to assume a day time heating time constant and night time cooling time constant.

Hence:

τ_h = 5min

τ_c = 7min

The MiCOM P438 also allows the thermal rating of the protection to be modified, based on signals from opto inputs. However, this facility is not used in this example.

9.9 Summary of catenary protection settings

The protection calculations for the catenary are now complete. The relay settings are summarised in Table C10.4.

Parameter	Symbol	Value
Zone 1 forward reach	$Z1_{fw}$	20.75 Ω
Zone 1 backward reach	$Z1_{rv}$	Blocked
Zone 2 forward reach	$Z2_{fw}$	36.1 Ω
Zone 2 backward reach	$Z2_{rv}$	Blocked
Zone 3 forward reach	$Z3_{fw}$	95.1 Ω
Zone 3 backward reach	$Z3_{rv}$	5.2 Ω
Zone 1 time delay	t_1	0s
Zone 2 time delay	t_2	160ms
Zone 3 time delay	t_3	500ms
Back-up overcurrent Instantaneous current setting	I'_{inst}	3.68A
Back-up overcurrent IDMT current setting	I'_{oc}	1.86A
Back-up overcurrent IDMT time delay setting	tI'_{oc}	250ms
Definite time overcurrent protection current setting	I'_{dtinst}	1.5A
Definite time overcurrent protection time delay setting	tI'_{dtinst}	800ms
Thermal protection reference current	I_{refs}	0.9A
Ambient temperature reference	t_{amb}	20°C
Thermal trip temperature	θ_{trip}	52°C
Thermal warning temperature	$\theta_{warning}$	44°C
Maximum ambient temperature	t_{ambmax}	28°C
Default ambient temperature	t_{ambdef}	20°C
Heating time constant - daytime	τ_h	5 min
Cooling time constant - nightime	τ_c	7 min

Table C10.4:
Electrified railway system example-relay settings