• 15 • Busbar Protection

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15.1 INTRODUCTION

The protection scheme for a power system should cover the whole system against all probable types of fault. Unrestricted forms of line protection, such as overcurrent and distance systems, meet this requirement, although faults in the busbar zone are cleared only after some time delay. But if unit protection is applied to feeders and plant, the busbars are not inherently protected.

Busbars have often been left without specific protection, for one or more of the following reasons:

a. the busbars and switchgear have a high degree of reliability, to the point of being regarded as intrinsically safe

b. it was feared that accidental operation of busbar protection might cause widespread dislocation of the power system, which, if not quickly cleared, would cause more loss than would the very infrequent actual bus faults

c. it was hoped that system protection or back-up protection would provide sufficient bus protection if needed

It is true that the risk of a fault occurring on modern metal-clad gear is very small, but it cannot be entirely ignored. However, the damage resulting from one uncleared fault, because of the concentration of fault MVA, may be very extensive indeed, up to the complete loss of the station by fire. Serious damage to or destruction of the installation would probably result in widespread and prolonged supply interruption.

Finally, system protection will frequently not provide the cover required. Such protection may be good enough for small distribution substations, but not for important stations. Even if distance protection is applied to all feeders, the busbar will lie in the second zone of all the distance protections, so a bus fault will be cleared relatively slowly, and the resultant duration of the voltage dip imposed on the rest of the system may not be tolerable.

With outdoor switchgear the case is less clear since, although the likelihood of a fault is higher, the risk of widespread damage resulting is much less. In general then, busbar protection is required when the system protection does not cover the busbars, or when, in order to maintain power system stability, high-speed fault clearance is necessary. Unit busbar protection provides this, with the further advantage that if the busbars are sectionalised, one section only need be isolated to clear a fault. The case for unit busbar protection is in fact strongest when there is sectionalisation.

15.2 BUSBAR FAULTS

The majority of bus faults involve one phase and earth, but faults arise from many causes and a significant number are interphase clear of earth. In fact, a large proportion of busbar faults result from human error rather than the failure of switchgear components.

With fully phase-segregated metalclad gear, only earth faults are possible, and a protection scheme need have earth fault sensitivity only. In other cases, an ability to respond to phase faults clear of earth is an advantage, although the phase fault sensitivity need not be very high.

15.3 PROTECTION REQUIREMENTS

Although not basically different from other circuit protection, the key position of the busbar intensifies the emphasis put on the essential requirements of speed and stability. The special features of busbar protection are discussed below.

15.3.1 Speed

Busbar protection is primarily concerned with:

a. limitation of consequential damage

b. removal of busbar faults in less time than could be achieved by back-up line protection, with the object of maintaining system stability

Some early busbar protection schemes used a low impedance differential system having a relatively long operation time, of up to 0.5 seconds. The basis of most modern schemes is a differential system using either low impedance biased or high impedance unbiased relays capable of operating in a time of the order of one cycle at a very moderate multiple of fault setting. To this must be added the operating time of the tripping relays, but an overall tripping time of less than two cycles can be achieved. With high-speed circuit breakers, complete fault clearance may be obtained in approximately 0.1 seconds. When a frame-earth system is used, the operating speed is comparable.

15.3.2 Stability

The stability of bus protection is of paramount importance. Bearing in mind the low rate of fault incidence, amounting to no more than an average of one fault per busbar in twenty years, it is clear that unless the stability of the protection is absolute, the degree of disturbance to which the power system is likely to be subjected may be increased by the installation of bus protection. The possibility of incorrect operation has, in the past, led to hesitation in applying bus protection and has also resulted in application of some very complex systems. Increased understanding of the response of differential systems to transient currents enables such systems to be applied with confidence in their fundamental stability. The theory of differential protection is given later in Section 15.7.

Notwithstanding the complete stability of a correctly applied protection system, dangers exist in practice for a number of reasons. These are:

a. interruption of the secondary circuit of a current transformer will produce an unbalance, which might cause tripping on load depending on the relative values of circuit load and effective setting. It would certainly do so during a through fault, producing substantial fault current in the circuit in question

b. a mechanical shock of sufficient severity may cause operation, although the likelihood of this occurring with modern numerical schemes is reduced

c. accidental interference with the relay, arising from a mistake during maintenance testing, may lead to operation

In order to maintain the high order of integrity needed for busbar protection, it is an almost invariable practice to make tripping depend on two independent measurements of fault quantities. Moreover, if the tripping of all the breakers within a zone is derived from common measuring relays, two separate elements must be operated at each stage to complete a tripping operation. Although not current practice, in many cases the relays are separated by about 2 metres so that no reasonable accidental mechanical interference to both relays simultaneously is possible.

The two measurements may be made by two similar differential systems, or one differential system may be checked by a frame-earth system, by earth fault relays energised by current transformers in the transformer neutral-earth conductors or by overcurrent relays. Alternatively, a frame-earth system may be checked by earth fault relays.

If two systems of the unit or other similar type are used, they should be energised by separate current transformers in the case of high impedance unbiased differential schemes. The duplicate ring CT cores may be mounted on a common primary conductor but independence must be maintained throughout the secondary circuit.

In the case of low impedance, biased differential schemes that cater for unequal ratio CT's, the scheme can be energised from either one or two separate sets of main current transformers. The criteria of double feature operation before tripping can be maintained by the provision of two sets of ratio matching interposing CT's per circuit. When multi-contact tripping relays are used, these are also duplicated, one being energised from each discriminating relay; the contacts of the tripping relay are then series-connected in pairs to provide tripping outputs.

Separate tripping relays, each controlling one breaker only, are usually preferred. The importance of such relays is then no more than that of normal circuit protection, so no duplication is required at this stage. Not least among the advantages of using individual tripping relays is the simplification of trip circuit wiring, compared with taking all trip circuits associated with a given bus section through a common multi-contact tripping relay.

In double busbar installations, a separate protection system is applied to each section of each busbar; an overall check system is provided, covering all sections of both busbars. The separate zones are arranged to overlap the busbar section switches, so that a fault on the section switch trips both the adjacent zones. This has sometimes been avoided in the past by giving the section switch a time advantage; the section switch is tripped first and the remaining breakers delayed by 0.5 seconds.

Only the zone on the faulty side of the section switch will remain operated and trip, the other zone resetting and retaining that section in service. This gain, applicable only to very infrequent section switch faults, is obtained at the expense of seriously delaying the bus protection for all other faults. This practice is therefore not generally favoured. Some variations are dealt with later under the more detailed scheme descriptions. There are many combinations possible, but the essential principle is that no single accidental incident of a secondary nature shall be capable of causing an unnecessary trip of a bus section.

Security against maloperation is only achieved by increasing the amount of equipment that is required to function to complete an operation; and this inevitably increases the statistical risk that a tripping operation due to a fault may fail. Such a failure, leaving aside the question of consequential damage, may result in disruption of the power system to an extent as great, or greater, than would be caused by an unwanted trip. The relative risk of failure of this kind may be slight, but it has been thought worthwhile in some instances to provide a guard in this respect as well.

Security of both stability and operation is obtained by providing three independent channels (say X, Y and Z) whose outputs are arranged in a 'two-out-of three' voting arrangement, as shown in Figure 15.1.

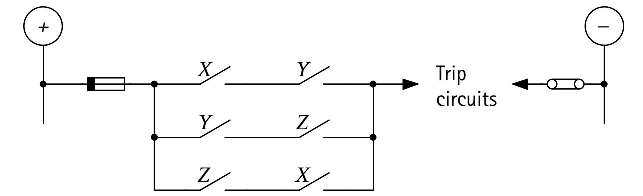

Figure 15.1: Two-out-of-three principle

15.4 TYPES OF PROTECTION SYSTEM

A number of busbar protection systems have been devised:

- **a.** system protection used to cover busbars
- **b.** frame-earth protection
- **c.** differential protection
- **d.** phase comparison protection
- **e.** directional blocking protection

Of these, (a) is suitable for small substations only, while (d) and (e) are obsolete. Detailed discussion of types (b) and (c) occupies most of this chapter.

Early forms of biased differential protection for busbars, such as versions of 'Translay' protection and also a scheme using harmonic restraint, were superseded by unbiased high impedance differential protection.

The relative simplicity of the latter, and more importantly the relative ease with which its performance can be calculated, have ensured its success up to the present day.

But more recently the advances in semiconductor technology, coupled with a more pressing need to be able to accommodate CT's of unequal ratio, have led to the re-introduction of biased schemes, generally using static relay designs, particularly for the most extensive and onerous applications.

Frame-earth protection systems have been in use for many years, mainly associated with smaller busbar protection schemes at distribution voltages and for metalclad busbars (e.g. SF6 insulated busbars). However, it has often been quite common for a unit protection scheme to be used in addition, to provide two separate means of fault detection.

The different types of protection are described in the following sections.

15.5 SYSTEM PROTECTION SCHEMES

System protection that includes overcurrent or distance systems will inherently give protection cover to the busbars. Overcurrent protection will only be applied to relatively simple distribution systems, or as a back-up protection, set to give a considerable time delay. Distance protection will provide cover for busbar faults with its second and possibly subsequent zones. In both cases the busbar protection obtained is slow and suitable only for limiting the consequential damage.

The only exception is the case of a mesh-connected substation, in which the current transformers are located at the circuit breakers. Here, the busbars are included, in sections, in the individual zones of the main circuit protection, whether this is of unit type or not. In the special case when the current transformers are located on the line side of the mesh, the circuit protection will not cover the busbars in the instantaneous zone and separate busbar protection, known as mesh-corner protection, is generally used – see Section 15.7.2.1 for details.

15.6 FRAME-EARTH PROTECTION (HOWARD PROTECTION)

Frame leakage protection has been extensively used in the past in many different situations. There are several variations of frame leakage schemes available, providing busbar protection schemes with different capabilities. The following sections schemes have thus been retained for historical and general reference purposes. A considerable number of schemes are still in service and frame leakage may provide an acceptable solution in particular circumstances. However, the need to insulate the switchboard frame and provide cable gland insulation and the availability of alternative schemes using numerical relays, has contributed to a decline in use of frame leakage systems.

15.6.1 Single-Busbar Frame-Earth Protection

This is purely an earth fault system and, in principle, involves simply measuring the fault current flowing from the switchgear frame to earth. A current transformer is mounted on the earthing conductor and is used to energize a simple instantaneous relay as shown in Figure 15.2.

No other earth connections of any type, including incidental connections to structural steelwork are allowed. This requirement is so that:

a. the principal earth connection and current transformer are not shunted, thereby raising the effective setting. An increased effective setting gives rise to the possibility of relay maloperation. This risk is small in practice

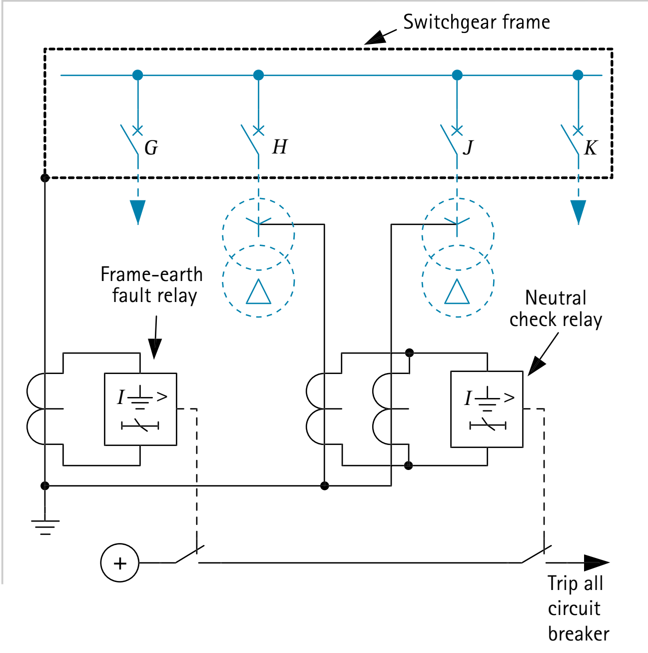

Figure 15.2: Single zone frame-earth protection

b. earth current flowing to a fault elsewhere on the system cannot flow into or out of the switchgear frame via two earth connections, as this might lead to a spurious operation

The switchgear must be insulated as a whole, usually by standing it on concrete. Care must be taken that the foundation bolts do not touch the steel reinforcement; sufficient concrete must be cut away at each hole to permit grouting-in with no risk of touching metalwork. The insulation to earth finally achieved will not be high, a value of 10 ohms being satisfactory.

When planning the earthing arrangements of a frame-leakage scheme, the use of one common electrode for both the switchgear frame and the power system neutral point is preferred, because the fault path would otherwise include the two earthing electrodes in series. If either or both of these are of high resistance or have inadequate current carrying capacity, the fault current may be limited to such an extent that the protection equipment becomes inoperative. In addition, if the electrode earthing the switchgear frame is the offender, the potential of the frame may be raised to a dangerous value. The use of a common earthing electrode of adequate rating and low resistance ensures sufficient current for scheme operation and limits the rise in frame potential. When the system is resistance earthed, the earthing connection from the switchgear frame is made between the bottom of the earthing resistor and the earthing electrode.

Figure 15.3 illustrates why a lower limit of 10 ohms insulation resistance between frame and earth is necessary.

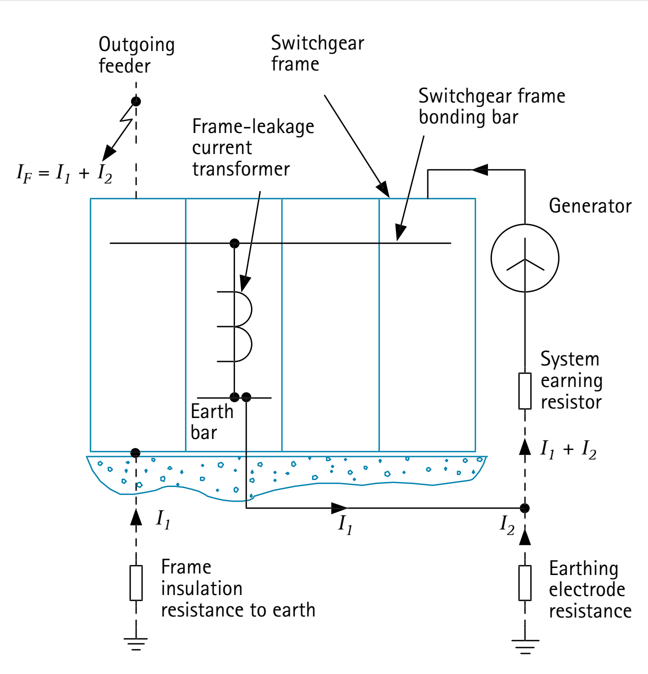

Figure 15.3: Current distribution for external fault

Under external fault conditions, the current I_1 flows through the frame-leakage current transformer. If the insulation resistance is too low, sufficient current may flow to operate the frame-leakage relay, and, as the check feature is unrestricted, this will also operate to complete the trip circuit. The earth resistance between the earthing electrode and true earth is seldom greater than 1Ω, so with 10Ω insulation resistance the current I_1 is limited to 10% of the total earth fault current I_1 and I_2. For this reason, the recommended minimum setting for the scheme is about 30% of the minimum earth fault current.

All cable glands must be insulated, to prevent the circulation of spurious current through the frame and earthing system by any voltages induced in the cable sheath. Preferably, the gland insulation should be provided in two layers or stages, with an interposing layer of metal, to facilitate the testing of the gland insulation. A test level of 5kV from each side is suitable.

15.6.2 Frame-Earth Protection - Sectioned Busbars

Section 15.6.1 covered the basic requirements for a system to protect switchgear as a whole. When the busbar is divided into sections, these can be protected separately, provided the frame is also sub-divided, the sections mutually insulated, and each provided with a separate earth conductor, current transformer and relay.

Ideally, the section switch should be treated as a separate zone, as shown in Figure 15.4, and provided with either a separate relay or two secondaries on the frame-leakage current transformer, with an arrangement to trip both adjacent zones. The individual zone relays trip their respective zone and the section switch.

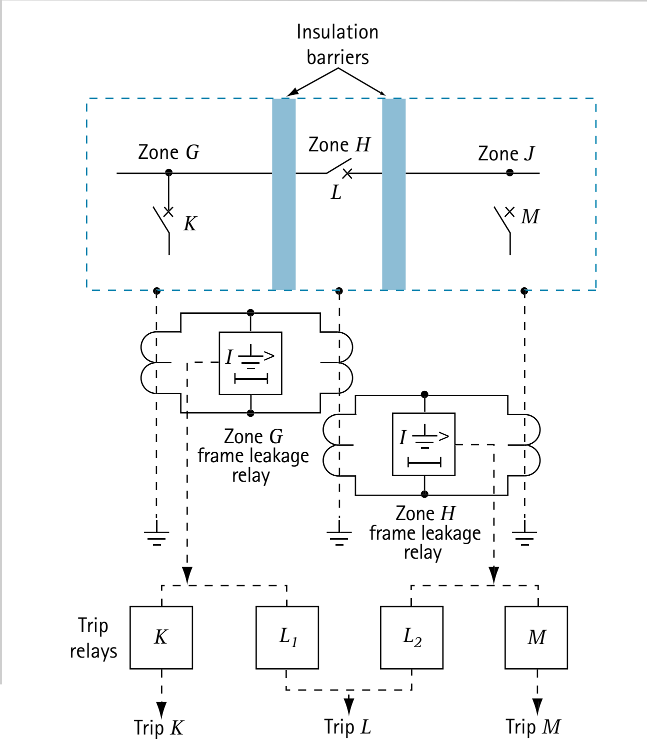

Figure 15.4: Three zone frame earth scheme

If it is inconvenient to insulate the section switch frame on one side, this switch may be included in that zone. It is then necessary to intertrip the other zone after approximately 0.5 seconds if a fault persists after the zone including the section switch has been tripped. This is illustrated in Figure 15.5.

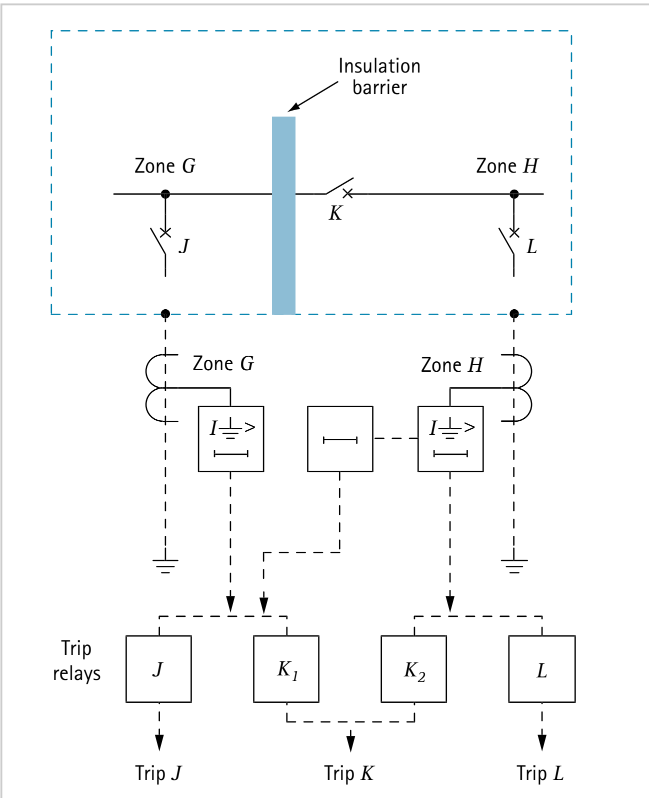

Figure 15.5: Frame-earth scheme: bus section breaker insulated on one side only

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For the above schemes to function it is necessary to have a least one infeed or earthed source of supply, and in the latter case it is essential that this source of supply be connected to the side of the switchboard not containing the section switch. Further, if possible, it is preferable that an earthed source of supply be provided on both sides of the switchboard, in order to ensure that any faults that may develop between the insulating barrier and the section switch will continue to be fed with fault current after the isolation of the first half of the switchboard, and thus allow the fault to be removed. Of the two arrangements, the first is the one normally recommended, since it provides instantaneous clearance of busbar faults on all sections of the switchboard.

15.6.3 Frame-Earth Scheme - Double Bus Substation

It is not generally feasible to separately insulate the metal enclosures of the main and auxiliary busbars. Protection is therefore generally provided as for single bus installations, but with the additional feature that circuits connected to the auxiliary bus are tripped for all faults, as shown in Figure 15.6.

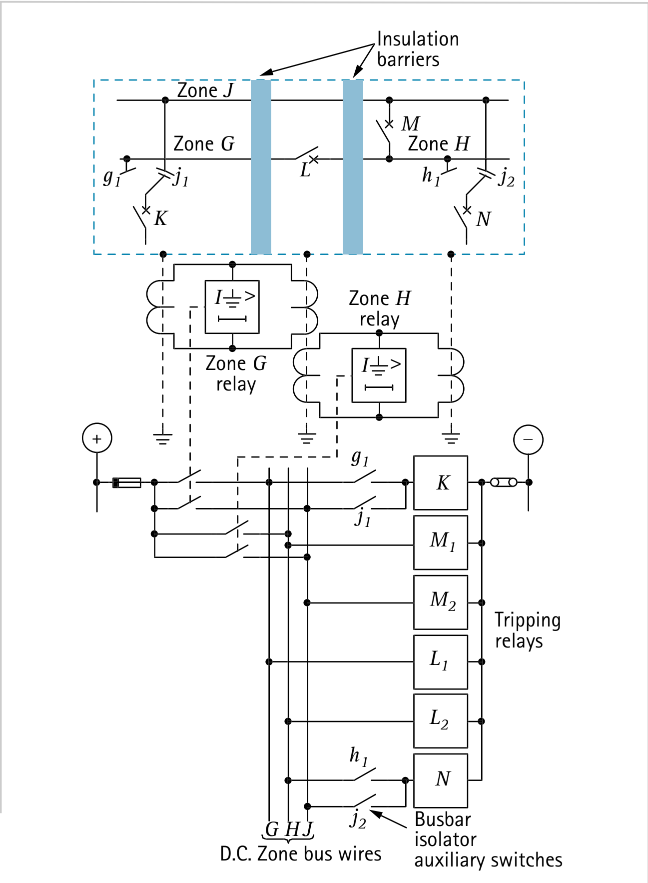


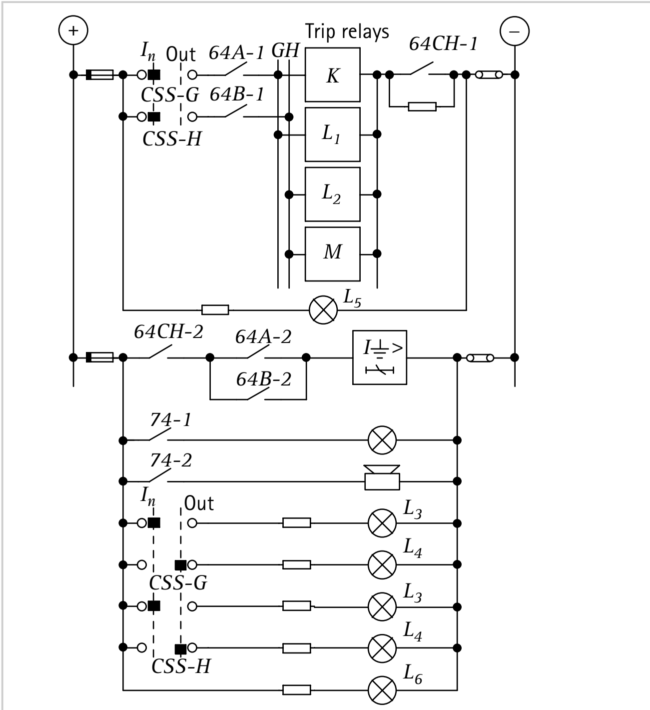
Figure 15.6: Frame-earth scheme for double busbar substation

15.6.4 Frame-Earth Protection - Check System

On all but the smallest equipments, a check system should be provided to guard against such contingencies as operation due to mechanical shock or mistakes made by personnel. Faults in the low voltage auxiliary wiring must also be prevented from causing operation by passing current to earth through the switchgear frame. A useful check is provided by a relay energised by the system neutral current, or residual current. If the neutral check cannot be provided, the frame-earth relays should have a short time delay.

When a check system is used, instantaneous relays can be used, with a setting of 30% of the minimum earth fault current and an operating time at five times setting of 15 milliseconds or less.

Figure 15.7 shows a frame-leakage scheme for a metalclad switchgear installation similar to that shown in Figure 15.4 and incorporating a neutral current check obtained from a suitable zero sequence current source, such as that shown in Figure 15.2.



74 Alarm cancellation relay
CSS Control selector switch protection in/protection out
L_3 Busbar protection in service lamp
L_4 Busbar protection out of service lamp
L_5 Tripping supply healthy lamp
L_6 Alarm and indication supply healthy lamp

Figure 15.7: Typical tripping and alarm circuits for a frame-leakage scheme

The protection relays used for the discriminating and check functions are of the attracted armature type, with two normally open self reset contacts. The tripping circuits cannot be complete unless both the discriminating and check relays operate; this is because the discriminating and check relay contacts are connected in series. The tripping relays are of the attracted armature type.

It is usual to supervise the satisfactory operation of the protection scheme with audible and visual alarms and indications for the following:

a. busbar faults

b. busbar protection in service

c. busbar protection out of service

d. tripping supply healthy

e. alarm supply healthy

To enable the protection equipment of each zone to be taken out of service independently during maintenance periods, isolating switches - one switch per zone - are provided in the trip supply circuits and an alarm cancellation relay is used.

15.7 DIFFERENTIAL PROTECTION PRINCIPLES

The Merz-Price principle is applicable to a multi-terminal zone such as a busbar. The principle is a direct application of Kirchhoff's first law. Usually, the circulating current arrangement is used, in which the current transformers and interconnections form an analogue of the busbar and circuit connections. A relay connected across the CT bus wires represents a fault path in the primary system in the analogue and hence is not energised until a fault occurs on the busbar; it then receives an input that, in principle at least, represents the fault current.

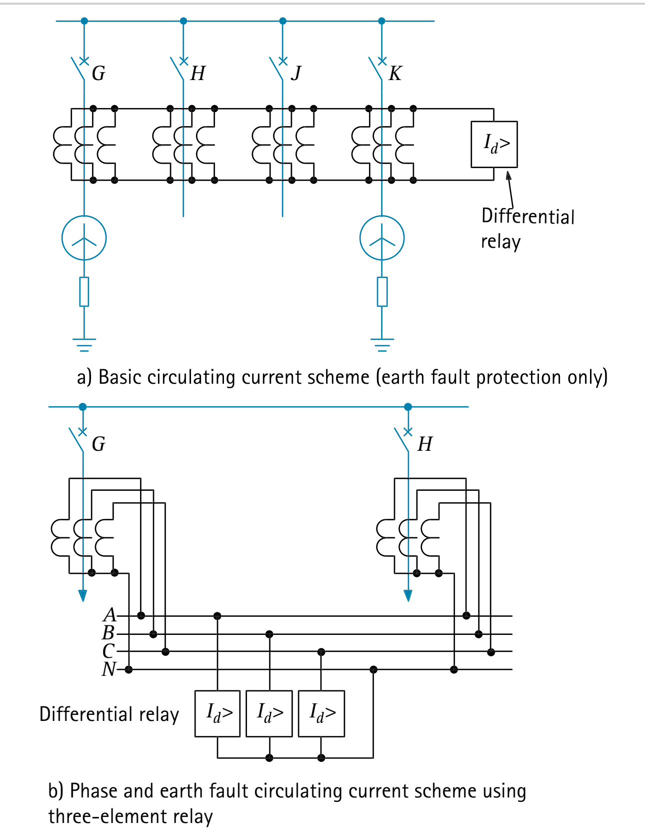


Figure 15.8: Circulating current scheme

The scheme may consist of a single relay connected to the bus wires connecting all the current transformers in parallel, one set per circuit, associated with a particular zone, as shown in Figure 15.8(a). This will give earth fault protection for the busbar. This arrangement has often been thought to be adequate.

If the current transformers are connected as a balanced group for each phase together with a three-element relay, as shown in Figure 15.8(b), additional protection for phase faults can be obtained.

The phase and earth fault settings are identical, and this scheme is recommended for its ease of application and good performance.

15.7.1 Differential Protection for Sectionalised and Duplicate Busbars

Each section of a divided bus is provided with a separate circulating current system. The zones so formed are over-lapped across the section switches, so that a fault on the latter will trip the two adjacent zones. This is illustrated in Figure 15.9.

Tripping two zones for a section switch fault can be avoided by using the time-delayed technique of Section 15.6.2. However instantaneous operation is the preferred choice.

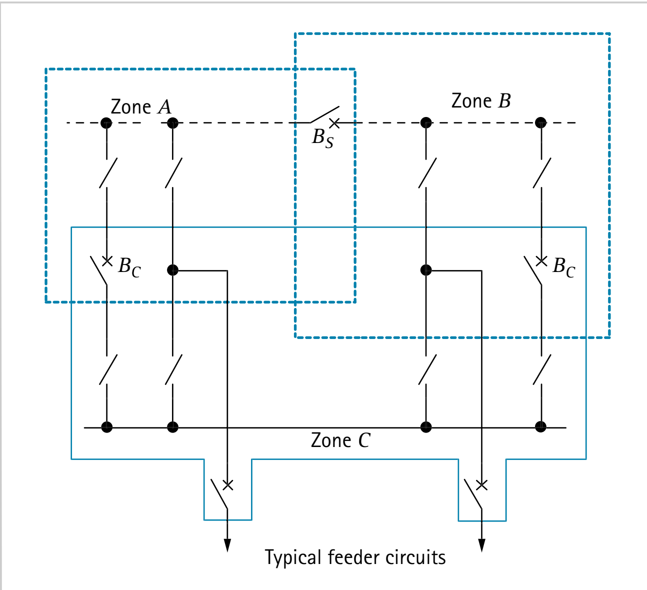


Figure 15.9: Zones of protection for double bus station

For double bus installation, the two busbars will be treated as separate zones. The auxiliary busbar zone will overlap the appropriate main busbar zone at the bus coupler.

Since any circuit may be transferred from one busbar to the other by isolator switches, these and the associated tripping circuit must also be switched to the appropriate zone by 'early make' and 'late break' auxiliary contacts. This is to ensure that when the isolators are closing, the auxiliary switches make before the main contacts of the isolator, and that when the isolators are opened, their main contacts part before the auxiliary switches open. The result is that the secondary circuits of the two zones concerned are briefly paralleled while the circuit is being transferred; these two zones have in any case been united through the circuit isolators during the transfer operation.

15.7.2 Location of Current Transformers

Ideally, the separate discriminating zones should overlap each other and also the individual circuit protections. The overlap should occur across a circuit breaker, so that the latter lies in both zones. For this arrangement it is necessary to install current transformers on both sides of the circuit breakers, which is economically possible with many but not all types of switchgear. With both the circuit and the bus protection current transformers on the same side of the circuit breakers, the zones may be overlapped at the current transformers, but a fault between the CT location and the circuit breaker will not be completely isolated. This matter is important in all switchgear to which these conditions apply, and is particularly important in the case of outdoor switchgear where separately mounted, multi-secondary current transformers are generally used. The conditions are shown in Figure 15.10.

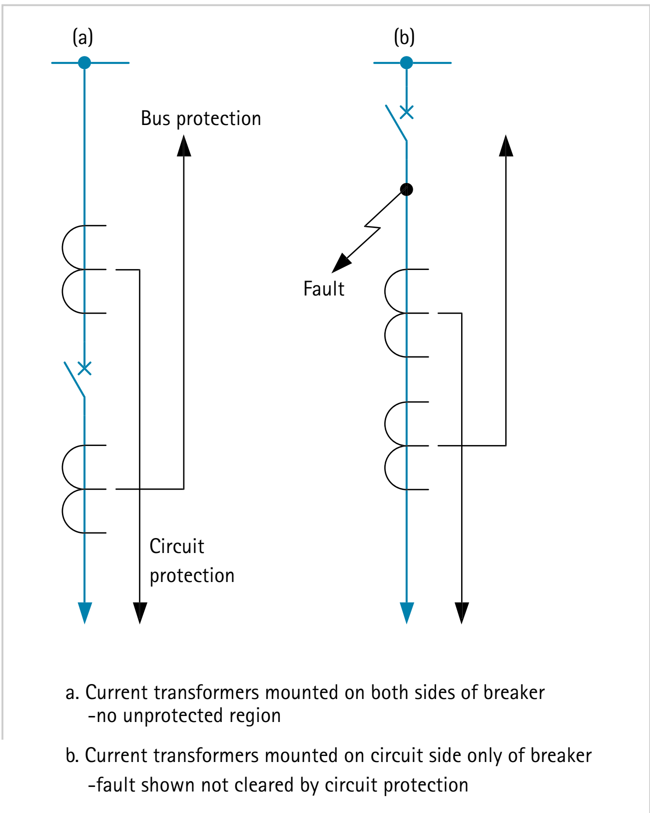


Figure 15.10: Unprotected zone with current transformers mounted on one side of the circuit breaker only

Figure 15.10(a) shows the ideal arrangement in which both the circuit and busbar zones are overlapped leaving no region of the primary circuit unprotected.

Figure 15.10(b) shows how mounting all current transformers on the circuit side of the breaker results in a small region of the primary circuit unprotected. This unprotected region is typically referred to as the 'short zone'. The fault shown will cause operation of the busbar protection, tripping the circuit breaker, but the fault will continue to be fed from the circuit, if a source of power is present. It is necessary for the bus protection to intertrip the far end of the circuit protection, if the latter is of the unit type.

With reference to Figure 15.10(b), special 'short zone' protection can be provided to detect that the circuit breaker has opened but that the fault current is still flowing. Under these conditions, the protection can initiate an intertrip to the remote end of the circuit. This technique may be used, particularly when the circuit includes a generator. In this case the intertrip proves that the fault is in the switchgear connections and not in the generator; the latter is therefore tripped electrically but not shut down on the mechanical side so as to be immediately ready for further service if the fault can be cleared.

15.7.2.1 CT locations for mesh-connected substations

The protection of busbars in mesh connected substations gives rise to additional considerations in respect of CT location. A single mesh corner is shown in Figure

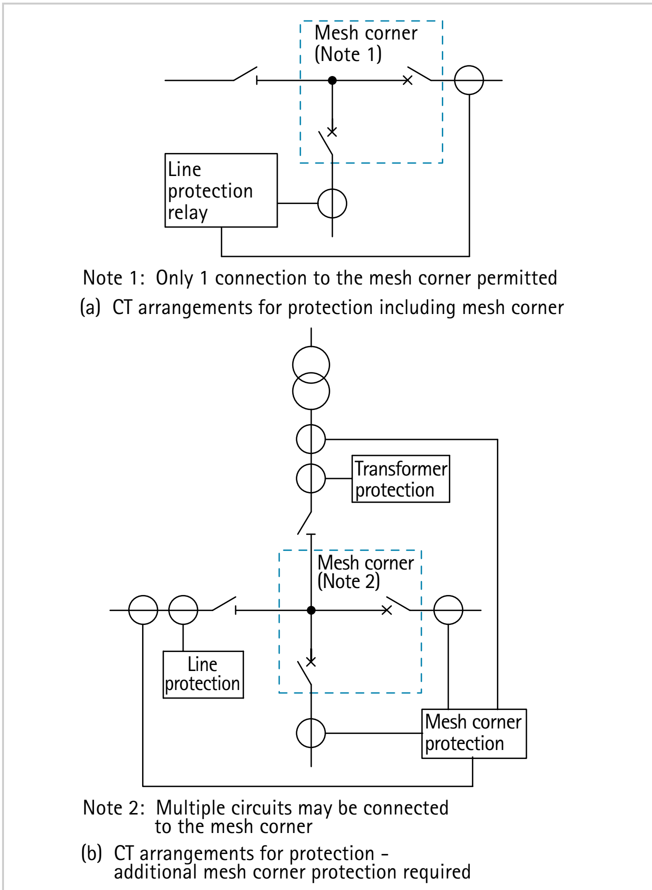


Figure 15.11: Mesh-corner protection

15.11(a). Where only one connection to the mesh is made at a corner, CT's located as shown will provide protection not only to the line but the corner of the mesh included between them. However, this arrangement cannot be used where more than one connection is made to a mesh corner. This is because a fault on any of the connected circuits would result in disconnection of them all, without any means of determining the faulted connection. Protection CT's must therefore be located on each connection, as shown in Figure 15.11(b). This leaves the corner of the mesh unprotected, so additional CT's and a relay to provide mesh-corner protection are added, as also shown in Figure 15.11(b).

15.8 HIGH IMPEDANCE DIFFERENTIAL PROTECTION

This form of protection is still in common use. The considerations that have to be taken into account are detailed in the following sections.

15.8.1 Stability

The incidence of fault current with an initial unilateral transient component causes an abnormal built-up of flux in a current transformer, as described in Section 6.4.10. When through-fault current traverses a zone protected by a differential system, the transient flux produced in the current transformers is not detrimental as long as it remains within the substantially linear range of the magnetising characteristic. With fault current of appreciable magnitude and long transient time constant, the flux density will pass into the saturated region of the characteristic; this will not in itself produce a spill output from a pair of balancing current transformers provided that these are identical and equally burdened. A group of current transformers, though they may be of the same design, will not be completely identical, but a more important factor is inequality of burden. In the case of a differential system for a busbar, an external fault may be fed through a single circuit, the current being supplied to the busbar through all other circuits. The faulted circuit is many times more heavily loaded than the others and the corresponding current transformers are likely to be heavily saturated, while those of the other circuits are not. Severe unbalance is therefore probable, which, with a relay of normal burden, could exceed any acceptable current setting. For this reason such systems were at one time always provided with a time delay. This practice is, however, no longer acceptable.

It is not feasible to calculate the spill current that may occur, but, fortunately, this is not necessary; an alternative approach provides both the necessary information and the technique required to obtain a high performance.

An equivalent circuit, as in Figure 15.12, can represent a circulating current system.

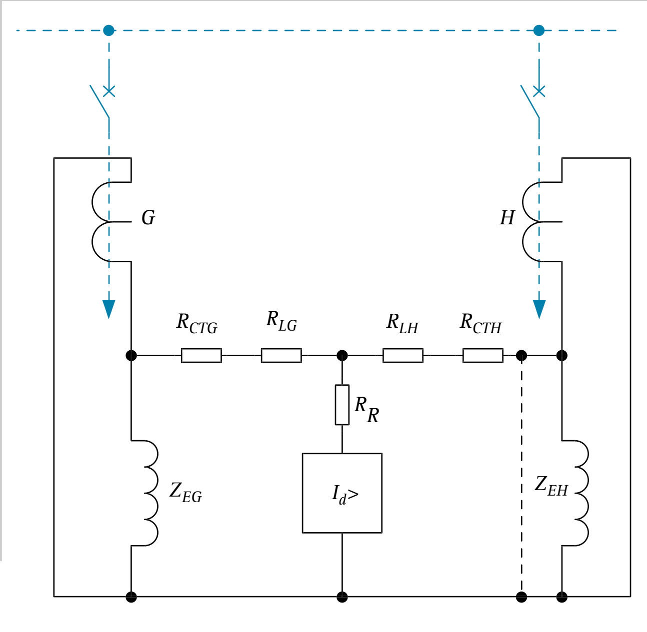


Figure 15.12: Equivalent circuit of circulating current system

The current transformers are replaced in the diagram by ideal current transformers feeding an equivalent circuit that represents the magnetising losses and secondary winding resistance, and also the resistance of the connecting leads. These circuits can then be interconnected as shown, with a relay connected to the junction points to form the complete equivalent circuit.

Saturation has the effect of lowering the exciting impedance, and is assumed to take place severely in current transformer H until, at the limit, the shunt impedance becomes zero and the CT can produce no output. This condition is represented by a short circuit, shown in broken line, across the exciting impedance. It should be noted that this is not the equivalent of a physical short circuit, since it is behind the winding resistance .

Applying the Thévenin method of solution, the voltage developed across the relay will be given by:

$$I_R = \frac{V_f}{R_R + R_{LH} + R_{CTH}} \quad \text{...Equation 15.1}$$

The current through the relay is given by:

$$= \frac{I_f\left(R_{LH} + R_{CTH}\right)}{R_R + R_{LH} + R_{CTH}} \quad \text{...Equation 15.2}$$

If R_R is small, I_R will approximate to I_F, which is unacceptable. On the other hand, if R_R is large I_R is reduced. Equation 15.2 can be written, with little error, as follows:

$$I_R = \frac{V_f}{R_R} = \frac{I_f\left(R_{LH} + R_{CTH}\right)}{R_R}$$ ...Equation 15.3

or alternatively:

$$I_R R_R = V_f = I_f\left(R_{LH} + R_{CTH}\right)$$ ...Equation 15.4

It is clear that, by increasing R_R, the spill current I_R can be reduced below any specified relay setting. R_R is frequently increased by the addition of a series-connected resistor which is known as the stabilising resistor.

It can also be seen from Equation 15.4 that it is only the voltage drop in the relay circuit at setting current that is important. The relay can be designed as a voltage measuring device consuming negligible current; and provided its setting voltage exceeds the value V_f of Equation 15.4, the system will be stable. In fact, the setting voltage need not exceed V_f, since the derivation of Equation 15.4 involves an extreme condition of unbalance between the G and H current transformers that is not completely realised. So a safety margin is built-in if the voltage setting is made equal to V_f.

It is necessary to realise that the value of I_f to be inserted in Equation 15.4 is the complete function of the fault current and the spill current I_R through the relay, in the limiting condition, will be of the same form. If the relay requires more time to operate than the effective duration of the d.c. transient component, or has been designed with special features to block the d.c. component, then this factor can be ignored and only the symmetrical value of the fault current need be entered in Equation 15.4. If the relay setting voltage, V_s, is made equal to V_f, that is, I_f $(R_L + R_{CT})$, an inherent safety factor of the order of two will exist.

In the case of a faster relay, capable of operating in one cycle and with no special features to block the d.c. component, it is the r.m.s. value of the first offset wave that is significant. This value, for a fully offset waveform with no d.c. decrement, is $\sqrt{3}I_f$. If settings are then chosen in terms of the symmetrical component of the fault current, the $\sqrt{3}$ factor which has been ignored will take up most of the basic safety factor, leaving only a very small margin.

Finally, if a truly instantaneous relay were used, the relevant value of I_f would be the maximum offset peak. In this case, the factor has become less than unity, possibly as low as 0.7. It is therefore possible to rewrite Equation 15.4 as:

$$I_{SL} = \frac{K \times V_S}{R_L + R_{CT}}$$ ...Equation 15.5

where:

I_{SL} = *stability of scheme*

V_S = *relay circuit voltage setting*

$R_L + R_{CT}$ = *lead + CT winding resistance*

K = *factor depending on relay design (range 0.7 - 2.0)*

It remains to be shown that the setting chosen is suitable.

The current transformers will have an excitation curve which has not so far been related to the relay setting voltage, the latter being equal to the maximum nominal voltage drop across the lead loop and the CT secondary winding resistance, with the maximum secondary fault current flowing through them. Under in-zone fault conditions it is necessary for the current transformers to produce sufficient output to operate the relay. This will be achieved provided the CT knee-point voltage exceeds the relay setting. In order to cater for errors, it is usual to specify that the current transformers should have a knee-point e.m.f. of at least twice the necessary setting voltage; a higher multiple is of advantage in ensuring a high speed of operation.

15.8.2 Effective Setting or Primary Operating Current

The minimum primary operating current is a further criterion of the design of a differential system. The secondary effective setting is the sum of the relay minimum operating current and the excitation losses in all parallel connected current transformers, whether carrying primary current or not. This summation should strictly speaking be vectorial, but is usually done arithmetically. It can be expressed as:

$$I_R = I_S + nI_{eS}$$ ...Equation 15.6

where:

I_R = *effective setting*

I_S = *relay circuit setting current*

I_{eS} = *CT excitation current at relay setting voltage*

n = *number of parallel - connected CT's*

Having established the relay setting voltage from stability considerations, as shown in Section 15.8.1, and knowing the excitation characteristic of the current transformers, the effective setting can be computed. The secondary setting is converted to the primary operating current by multiplying by the turns ratio of the current transformers. The operating current so determined should be considered in terms of the conditions of the application.

For a phase and earth fault scheme the setting can be based on the fault current to be expected for minimum plant and maximum system outage conditions. However, it should be remembered that:

a. phase-phase faults give only 86% of the three-phase fault current

b. fault arc resistance and earth path resistance reduce fault currents somewhat

c. a reasonable margin should be allowed to ensure that relays operate quickly and decisively

It is desirable that the primary effective setting should not exceed 30% of the prospective minimum fault current.

In the case of a scheme exclusively for earth fault protection, the minimum earth fault current should be considered, taking into account any earthing impedance that might be present as well. Furthermore, in the event of a double phase to earth fault, regardless of the inter-phase currents, only 50% of the system e.m.f. is available in the earth path, causing a further reduction in the earth fault current. The primary operating current must therefore be not greater than 30% of the minimum single-phase earth fault current. In order to achieve high-speed operation, it is desirable that settings should be still lower, particularly in the case of the solidly earthed power system. The transient component of the fault current in conjunction with unfavourable residual flux in the CT can cause a high degree of saturation and loss of output, possibly leading to a delay of several cycles additional to the natural operating time of the element. This will not happen to any large degree if the fault current is a larger multiple of setting; for example, if the fault current is five times the scheme primary operating current and the CT knee-point e.m.f. is three times the relay setting voltage, the additional delay is unlikely to exceed one cycle.

The primary operating current is sometimes designed to exceed the maximum expected circuit load in order to reduce the possibility of false operation under load current as a result of a broken CT lead. Desirable as this safeguard may be, it will be seen that it is better not to increase the effective current setting too much, as this will sacrifice some speed; the check feature in any case, maintains stability.

An overall earth fault scheme for a large distribution board may be difficult to design because of the large number of current transformers paralleled together, which may lead to an excessive setting. It may be advantageous in such a case to provide a three-element phase and earth fault scheme, mainly to reduce the number of current transformers paralleled into one group.

Extra-high-voltage substations usually present no such problem. Using the voltage-calibrated relay, the current consumption can be very small.

A simplification can be achieved by providing one relay per circuit, all connected to the CT paralleling buswires.

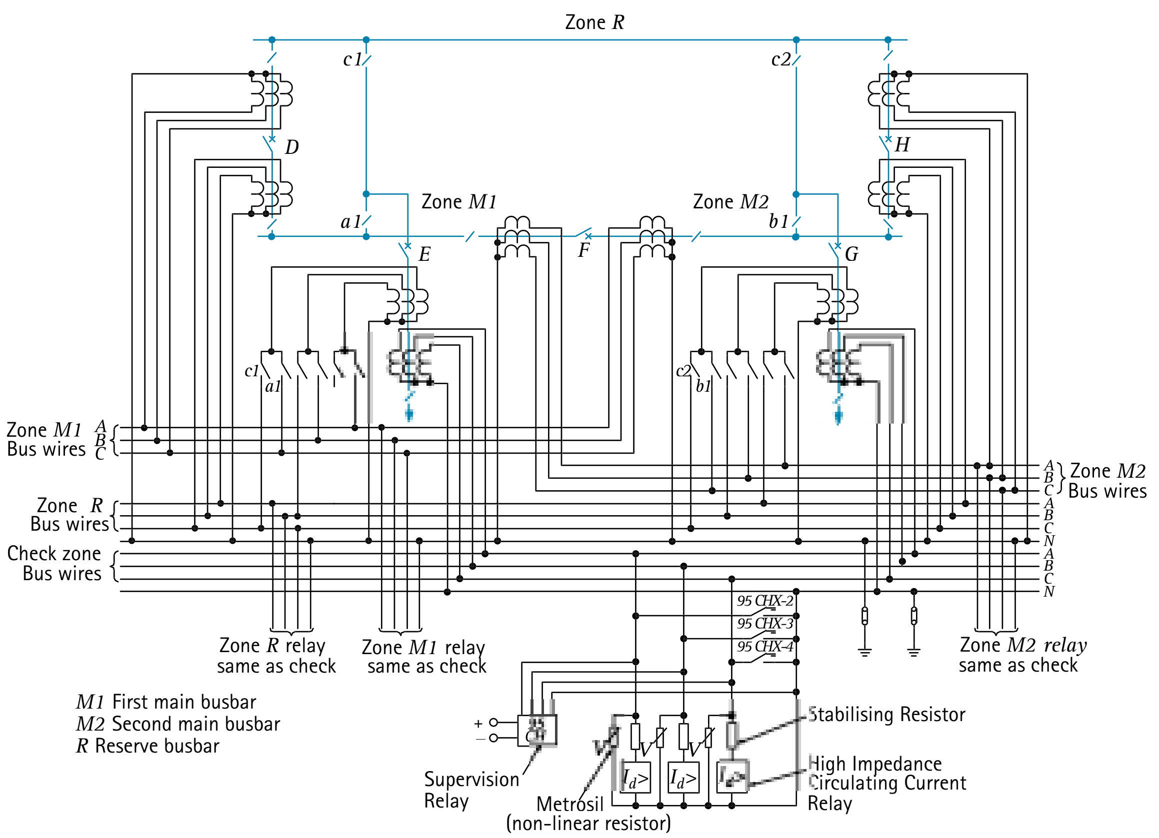
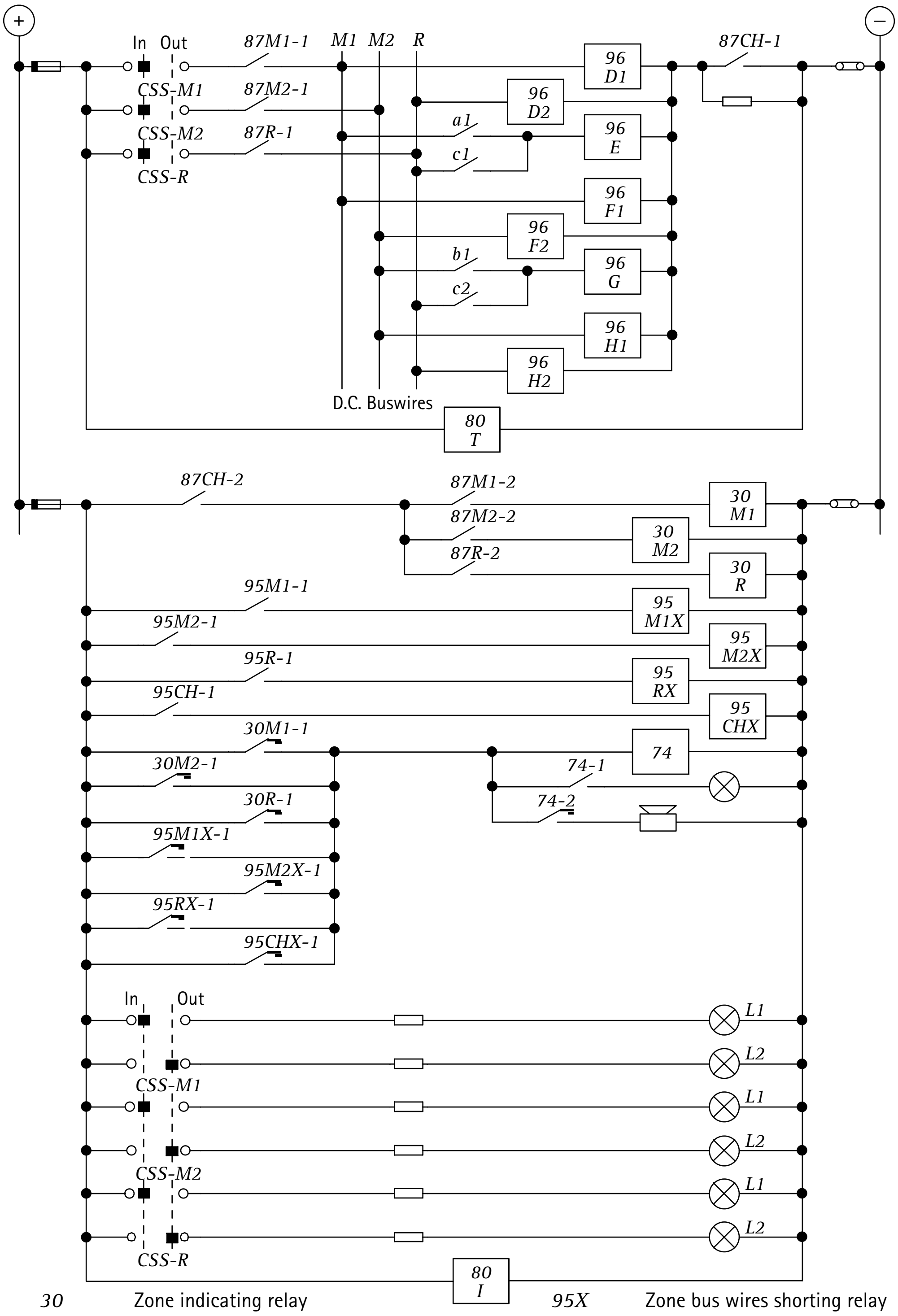


Figure 15.13: A.C. circuits for high impedance circulating current scheme for duplicate busbars



30	Zone indicating relay	*95X*	Zone bus wires shorting relay
74	Alarm cancellation relay	*CSS*	Control selector switch
80	D.C. volts supervision relay	*L1*	Indicating lamp protection in service
87	High impedance circulating current relay	*L2*	Indicating lamp protection out of service
95	Bus wires supervision relay		

Figure 15.14: D.C. circuits for high impedance circulating current scheme

This enables the trip circuits to be confined to the least area and reduces the risk of accidental operation.

15.8.3 Check Feature

Schemes for earth faults only can be checked by a frame-earth system, applied to the switchboard as a whole, no subdivision being necessary. For phase fault schemes, the check will usually be a similar type of scheme applied to the switchboard as a single overall zone.

A set of current transformers separate from those used in the discriminating zones should be provided. No CT switching is required and no current transformers are needed for the check zone in bus-coupler and bus-section breakers.

15.8.4 Supervision of CT Secondary Circuits

Any interruption of a CT secondary circuit up to the paralleling interconnections will cause an unbalance in the system, equivalent to the load being carried by the relevant primary circuit. Even though this degree of spurious output is below the effective setting the condition cannot be ignored, since it is likely to lead to instability under any through fault condition.

Supervision can be carried out to detect such conditions by connecting a sensitive alarm relay across the bus wires of each zone. For a phase and earth fault scheme, an internal three-phase rectifier can be used to effect a summation of the bus wire voltages on to a single alarm element; see Figures 15.13 and 15.14.

The alarm relay is set so that operation does not occur with the protection system healthy under normal load. Subject to this proviso, the alarm relay is made as sensitive as possible; the desired effective setting is 125 primary amperes or 10% of the lowest circuit rating, whichever is the greater.

Since a relay of this order of sensitivity is likely to operate during through faults, a time delay, typically of three seconds, is applied to avoid unnecessary alarm signals.

15.8.5 Arrangement of CT Connections

It is shown in Equation 15.4 how the setting voltage for a given stability level is directly related to the resistance of the CT secondary leads. This should therefore be kept to a practical minimum. Taking into account the practical physical laying of auxiliary cables, the CT bus wires are best arranged in the form of a ring around the switchgear site.

In a double bus installation, the CT leads should be taken directly to the isolator selection switches. The usual routing of cables on a double bus site is as follows:

a. current transformers to marshalling kiosk

b. marshalling kiosk to bus selection isolator auxiliary switches

c. interconnections between marshalling kiosks to form a closed ring

The relay for each zone is connected to one point of the ring bus wire. For convenience of cabling, the main zone relays will be connected through a multicore cable between the relay panel and the bus section-switch marshalling cubicle. The reserve bar zone and the check zone relays will be connected together by a cable running to the bus coupler circuit breaker marshalling cubicle. It is possible that special circumstances involving onerous conditions may over-ride this convenience and make connection to some other part of the ring desirable.

Connecting leads will usually be not less than 7/0.67mm (2.5mm^2), but for large sites or in other difficult circumstances it may be necessary to use cables of, for example 7/1.04mm (6mm^2) for the bus wire ring and the CT connections to it. The cable from the ring to the relay need not be of the larger section.

When the reserve bar is split by bus section isolators and the two portions are protected as separate zones, it is necessary to common the bus wires by means of auxiliary contacts, thereby making these two zones into one when the section isolators are closed.

15.8.6 Summary of Practical Details

This section provides a summary of practical considerations when implementing a high-impedance busbar protection scheme.

15.8.6.1 Designed stability level

For normal circumstances, the stability level should be designed to correspond to the switchgear rating; even if the available short-circuit power in the system is much less than this figure, it can be expected that the system will be developed up to the limit of rating.

15.8.6.2 Current transformers

Current transformers must have identical turns ratios, but a turns error of one in 400 is recognised as a reasonable manufacturing tolerance. Also, they should preferably be of similar design; where this is not possible the magnetising characteristics should be reasonably matched.

Current transformers for use with high impedance protection schemes should meet the requirements of Class PX of IEC 60044-1.

15.8.6.3 Setting voltage

The setting voltage is given by the equation

$$V_s > I_f (R_L + R_{CT})$$

where:

V_s = *relay circuit voltage setting*

I_f = *steady-state through fault current*

R_L = *CT lead loop resistence*

R_{CT} = *CT secondary winding resistance*

15.8.6.4 Knee-point voltage of current transformers

This is given by the formula

$$V_K \geq 2V_s$$

15.8.6.5 Effective setting (secondary)

The effective setting of the relay is given by

$$I_R = I_S + nI_{eS}I_R$$

where:

I_S = *relay circuit current setting*

I_{eS} = *CT excitation current at voltage setting*

n = *number of CT's in parallel*

For the primary fault setting multiply I_R by the CT turns ratio.

15.8.6.6 Current transformer secondary rating

It is clear from Equations 15.4 and 15.6 that it is advantageous to keep the secondary fault current low; this is done by making the CT turns ratio high. It is common practice to use current transformers with a secondary rating of 1A.

It can be shown that there is an optimum turns ratio for the current transformers; this value depends on all the application parameters but is generally about 2000/1. Although a lower ratio, for instance 400/1, is often employed, the use of the optimum ratio can result in a considerable reduction in the physical size of the current transformers.

15.8.6.7 Peak voltage developed by current transformers

Under in-zone fault conditions, a high impedance relay constitutes an excessive burden to the current transformers, leading to the development of a high voltage; the voltage waveform will be highly distorted but the peak value may be many times the nominal saturation voltage.

When the burden resistance is finite although high, an approximate formula for the peak voltage is:

$$V_P = 2\sqrt{2V_K\left(V_F - V_K\right)} \qquad \text{...Equation 15.7}$$

where:

V_P = *peak voltage developed*

V_K = *knee-point voltage*

V_F = *prospective voltage in absence of saturation*

This formula does not hold for the open circuit condition and is inaccurate for very high burden resistances that approximate to an open circuit, because simplifying assumptions used in the derivation of the formula are not valid for the extreme condition.

Another approach applicable to the open circuit secondary condition is:

$$V_P = \sqrt{2}\,\frac{I_f}{I_{ek}}\,V_K \qquad \text{...Equation 15.8}$$

where:

I_f = *fault current*

I_{ek} = *exciting current at knee - point voltage*

V_K = *knee - point voltage*

Any burden connected across the secondary will reduce the voltage, but the value cannot be deduced from a simple combination of burden and exciting impedances.

These formulae are therefore to be regarded only as a guide to the possible peak voltage. With large current transformers, particularly those with a low secondary current rating, the voltage may be very high, above a suitable insulation voltage. The voltage can be limited without detriment to the scheme by connecting a ceramic non-linear resistor in parallel with the relay having a characteristic given by:

$$V = CI^{\beta}$$

where C is a constant depending on dimensions and β is a constant in the range 0.2-0.25.

The current passed by the non-linear resistor at the relay voltage setting depends on the value of C; in order to keep the shunting effect to a minimum it is recommended to use a non-linear resistor with a value of C of 450 for relay voltages up to 175V and one with a value of C of 900 for setting voltages up to 325V.

15.8.6.8 High impedance relay

Instantaneous attracted armature relays are used. Simple fast-operating relays would have a low safety factor constant in the stability equation, Equation 15.5, as discussed in Section 15.8.1. The performance is improved by series-tuning the relay coil, thereby making the circuit resistive in effect. Inductive reactance would tend to reduce stability, whereas the action of capacitance is to block the unidirectional transient component of fault current and so raise the stability constant.

An alternative technique used in some relays is to apply the limited spill voltage principle shown in Equation 15.4. A tuned element is connected via a plug bridge to a chain of resistors; and the relay is calibrated in terms of voltage.

15.9 LOW IMPEDANCE BIASED DIFFERENTIAL PROTECTION

The principles of low impedance differential protection have been described in Section 10.4, including the principle advantages to be gained by the use of a bias technique. Most modern busbar protection schemes use this technique.

The principles of a check zone, zone selection, and tripping arrangements can still be applied. Current transformer secondary circuits are not switched directly by isolator contacts but instead by isolator repeat relays after a secondary stage of current transformation. These switching relays form a replica of the busbar within the protection and provide the complete selection logic.

15.9.1 Stability

With some biased relays, the stability is not assured by the through current bias feature alone, but is enhanced by the addition of a stabilising resistor, having a value which may be calculated as follows.

The through current will increase the effective relay minimum operating current for a biased relay as follows:

$$I_R = I_S + BI_F$$

where:

I_R = *effective minimum oprating current*

I_S = *relay setting current*

I_F = *through fault current*

B = *percentage restraint*

As I_F is generally much greater than I_S, the relay effective current, $I_R = BI_F$ approximately.

From Equation 15.4, the value of stabilising resistor is given by:

$$R_R = \frac{I_f\left(R_{LH} + R_{CTH}\right)}{I_R}$$

$$= \frac{R_{LH} + R_{CTH}}{B}$$

It is interesting to note that the value of the stabilising resistance is independent of current level, and that there would appear to be no limit to the through faults stability level. This has been identified [15.1] as 'The Principle of Infinite Stability'.

The stabilising resistor still constitutes a significant burden on the current transformers during internal faults.

An alternative technique, used by the MBCZ system described in Section 15.9.6, is to block the differential measurement during the portion of the cycle that a current transformer is saturated. If this is achieved by momentarily short-circuiting the differential path, a very low burden is placed on the current transformers. In this way the differential circuit of the relay is prevented from responding to the spill current.

It must be recognised though that the use of any technique for inhibiting operation, to improve stability performance for through faults, must not be allowed to diminish the ability of the relay to respond to internal faults.

15.9.2 Effective Setting or Primary Operating Current

For an internal fault, and with no through fault current flowing, the effective setting (I_R) is raised above the basic relay setting (I_S) by whatever biasing effect is produced by the sum of the CT magnetising currents flowing through the bias circuit. With low impedance biased differential schemes particularly where the busbar installation has relatively few circuits, these magnetising currents may be negligible, depending on the value of I_S.

The basic relay setting current was formerly defined as the minimum current required solely in the differential circuit to cause operation – Figure 15.15(a). This approach simplified analysis of performance, but was considered to be unrealistic, as in practice any current flowing in the differential circuit must flow in at least one half of the relay bias circuit causing the practical minimum operating current always to be higher than the nominal basic setting current. As a result, a later definition, as shown in Figure 15.15(b) was developed.

Conversely, it needs to be appreciated that applying the later definition of relay setting current, which flows through at least half the bias circuit, the notional minimum operation current in the differential circuit alone is somewhat less, as shown in Figure 15.15(b).
Using the definition presently applicable, the effective minimum primary operating current

$$= N\left[I_S + B\sum I_{eS}\right]$$

where:

$$N = CT\ ratio$$

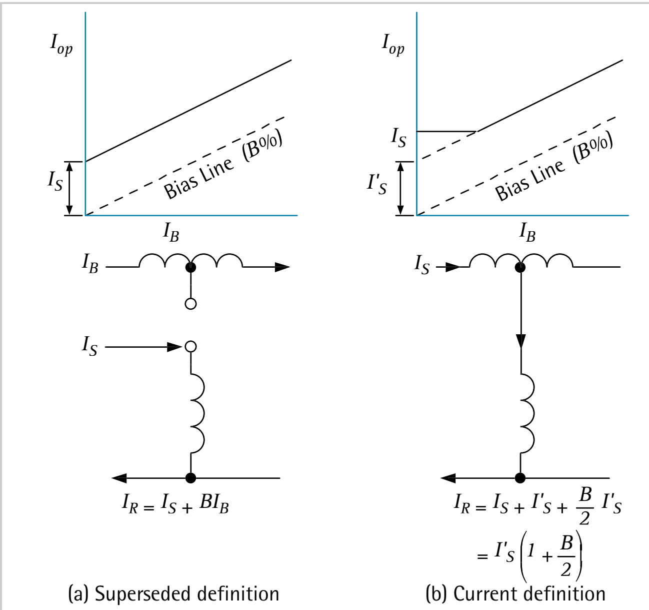


Figure 15.15: Definitions of relay setting current for biased relays

Unless the minimum effective operating current of a scheme has been raised deliberately to some preferred value, it will usually be determined by the check zone, when present, as the latter may be expected to involve the greatest number of current transformers in parallel. A slightly more onerous condition may arise when two discriminating zones are coupled, transiently or otherwise, by the closing of primary isolators.

It is generally desirable to attain an effective primary operating current that is just greater than the maximum load current, to prevent the busbar protection from operating spuriously from load current should a secondary circuit wiring fault develop. This consideration is particularly important where the check feature is either not used or is fed from common main CT's.

15.9.3 Check Feature

For some low impedance schemes, only one set of main CT's is required. This seems to contradict the general principle of all busbar protection systems with a check feature that complete duplication of all equipment is required, but it is claimed that the spirit of the checking principle is met by making operation of the protection dependent on two different criteria such as directional and differential measurements.

In the MBCZ scheme, described in Section 15.9.6, the provision of auxiliary CT's as standard for ratio matching also provides a ready means for introducing the check feature duplication at the auxiliary CT's and onwards to the relays. This may be an attractive compromise when only one set of main CT's is available.

15.9.4 Supervision of CT Secondary Circuits

In low impedance schemes the integrity of the CT secondary circuits can also be monitored. A current operated auxiliary relay, or element of the main protection equipment, may be applied to detect any unbalanced secondary currents and give an alarm after a time delay. For optimum discrimination, the current setting of this supervision relay must be less than that of the main differential protection.

In modern busbar protection schemes, the supervision of the secondary circuits typically forms only a part of a comprehensive supervision facility.

15.9.5 Arrangement of CT connections

It is a common modern requirement of low impedance schemes that none of the main CT secondary circuits should be switched, in the previously conventional manner, to match the switching of primary circuit isolators.

The usual solution is to route all the CT secondary circuits back to the protection panel or cubicle to auxiliary CT's. It is then the secondary circuits of the auxiliary CT's that are switched as necessary. So auxiliary CT's may be included for this function even when the ratio matching is not in question.

In static protection equipment it is undesirable to use isolator auxiliary contacts directly for the switching without some form of insulation barrier. Position transducers that follow the opening and closing of the isolators may provide the latter.

Alternatively, a simpler arrangement may be provided on multiple busbar systems where the isolators switch the auxiliary current transformer secondary circuits via auxiliary relays within the protection. These relays form a replica of the busbar and perform the necessary logic. It is therefore necessary to route all the current transformer secondary circuits to the relay to enable them to be connected into this busbar replica.

Some installations have only one set of current transformers available per circuit. Where the facility of a check zone is still required, this can still be achieved with the low impedance biased protection by connecting the auxiliary current transformers at the input of the main and check zones in series, as shown in Figure 15.16.

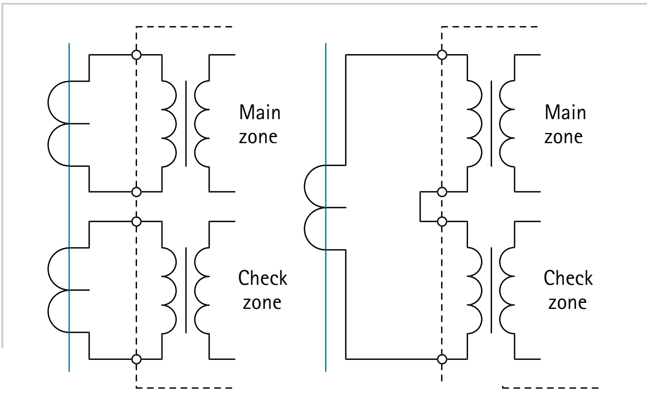


Figure 15.16: Alternative CT connections

15.9.6 Static Low Impedance Biased Differential Protection – Type MBCZ

The Type MBCZ scheme conforms in general to the principles outlined earlier and comprises a system of standard modules that can be assembled to suit a particular busbar installation. Additional modules can be added at any time as the busbar is extended.

A separate module is used for each circuit breaker and also one for each zone of protection. In addition to these there is a common alarm module and a number of power supply units. Ratio correction facilities are provided within each differential module to accommodate a wide range of CT mismatch.

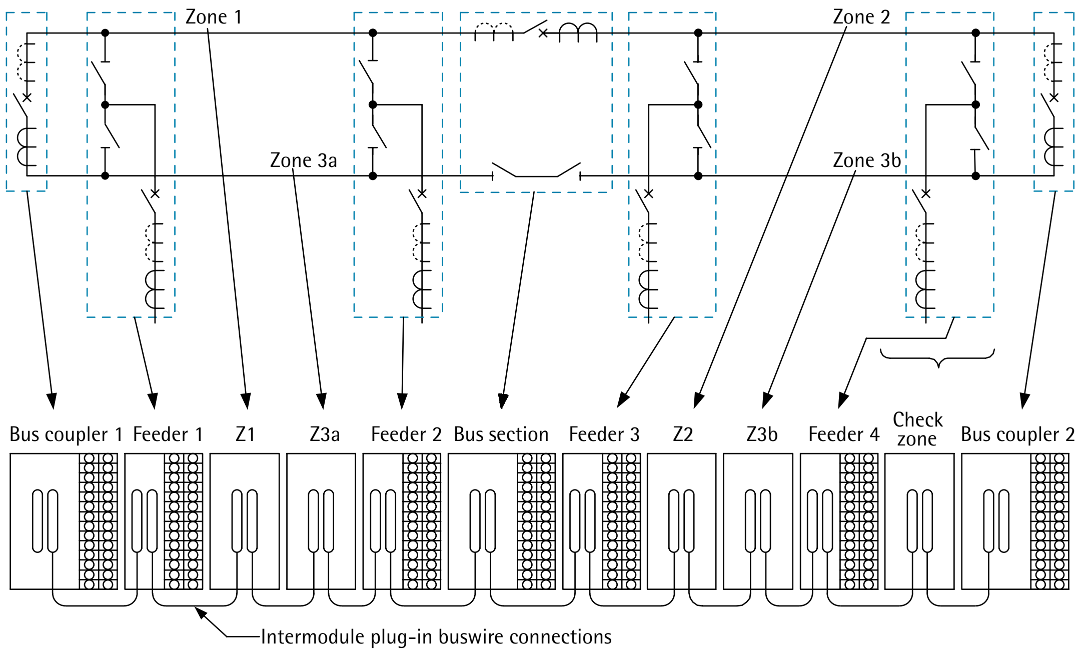


Figure 15.17: Type MBCZ busbar protection showing correlation between circuit breakers and protection modules

Figure 15.17 shows the correlation between the circuit breakers and the protection modules for a typical double busbar installation. In practice the modules are mounted in a multi-tier rack or cubicle.

The modules are interconnected via a multicore cable that is plugged into the back of the modules. There are five main groups of buswires, allocated for:

i. protection for main busbar

ii. protection for reserve busbar

iii. protection for the transfer busbar. When the reserve busbar is also used as a transfer bar then this group of buswires is used

iv. auxiliary connections used by the protection to combine modules for some of the more complex busbar configurations

v. protection for the check zone

One extra module, not shown in this diagram, is plugged into the multicore bus. This is the alarm module, which contains the common alarm circuits and the bias resistors. The power supplies are also fed in through this module.

15.9.6.1 Bias

All zones of measurement are biased by the total current flowing to or from the busbar system via the feeders. This ensures that all zones of measurement will have similar fault sensitivity under all load conditions. The bias is derived from the check zone and fixed at 20% with a characteristic generally as shown in Figure 15.15(b). Thus some ratio mismatch is tolerable.

15.9.6.2 Stability with saturated current transformers

The traditional method for stabilising a differential relay is to add a resistor to the differential path. Whilst this improves stability it increases the burden on the current transformer for internal faults. The technique used in the MBCZ scheme overcomes this problem.

The MBCZ design detects when a CT is saturated and short-circuits the differential path for the portion of the cycle for which saturation occurs. The resultant spill current does not then flow through the measuring circuit and stability is assured.

This principle allows a very low impedance differential circuit to be developed that will operate successfully with relatively small CT's.

15.9.6.3 Operation for internal faults

If the CT's carrying fault current are not saturated there will be ample current in the differential circuit to operate the differential relay quickly for fault currents exceeding the minimum operating level, which is adjustable between 20%-200% rated current.

When the only CT(s) carrying internal fault current become saturated, it might be supposed that the CT saturation detectors may completely inhibit operation by short-circuiting the differential circuit. However, the resulting inhibit pulses remove only an insignificant portion of the differential current, so operation of the relay is therefore virtually unaffected.

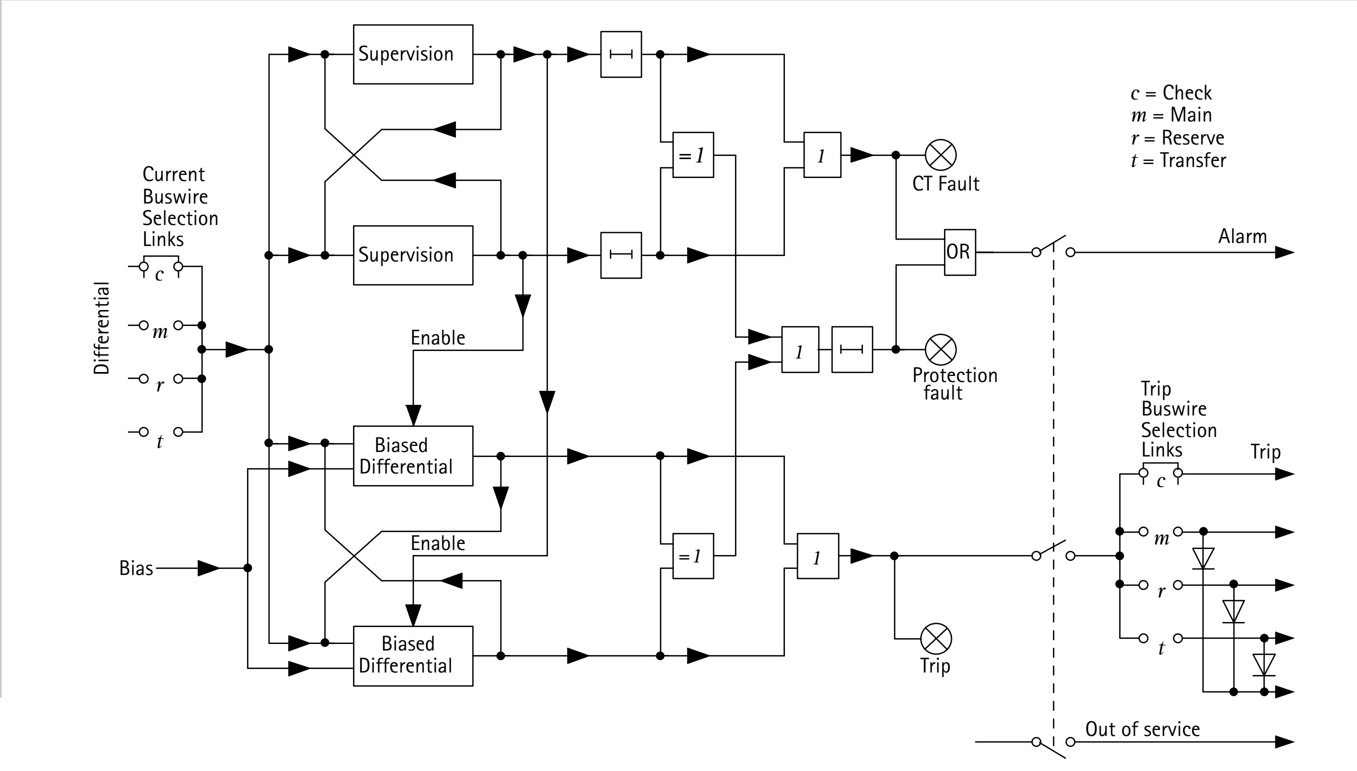


Figure 15.18: Block diagram of measuring unit

15.9.6.4 Discrepancy alarm feature

As shown in Figure 15.18, each measuring module contains duplicated biased differential elements and also a pair of supervision elements, which are a part of a comprehensive supervision facility.

This arrangement provides supervision of CT secondary circuits for both open circuit conditions and any impairment of the element to operate for an internal fault, without waiting for an actual system fault condition to show this up. For a zone to operate it is necessary for both the differential supervision element and the biased differential element to operate. For a circuit breaker to be tripped it requires the associated main zone to be operated and also the overall check zone, as shown in Figure 15.19.

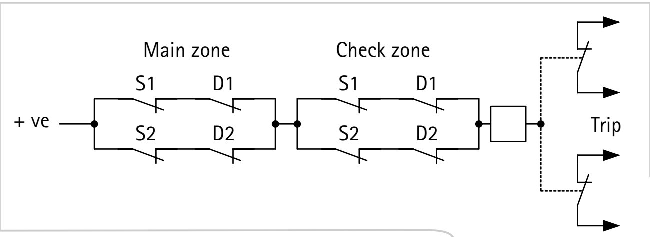


Figure 15.19: Busbar protection trip logic

15.9.6.5 Master/follower measuring units

When two sections of a busbar are connected together by isolators it will result in two measuring elements being connected in parallel when the isolators are closed to operate the two busbar sections as a single bar. The fault current will then divide between the two measuring elements in the ratio of their impedances. If both of the two measuring elements are of low and equal impedance the effective minimum operating current of the scheme will be doubled.

This is avoided by using a 'master/follower' arrangement. By making the impedance of one of the measuring elements very much higher than the other it is possible to ensure that one of the relays retains its original minimum operation current. Then to ensure that both the parallel-connected zones are tripped the trip circuits of the two zones are connected in parallel. Any measuring unit can have the role of 'master' or 'follower' as it is selectable by means of a switch on the front of the module.

15.9.6.6 Transfer tripping for breaker failure

Serious damage may result, and even danger to life, if a circuit breaker fails to open when called upon to do so. To reduce this risk breaker fail protection schemes were developed some years ago.

These schemes are generally based on the assumption that if current is still flowing through the circuit breaker a set time after the trip command has been issued, then it has failed to function. The circuit breakers in the next stage back in the system are then automatically tripped.

For a bus coupler or section breaker this would involve tripping all the infeeds to the adjacent zone, a facility that is included in the busbar protection scheme.

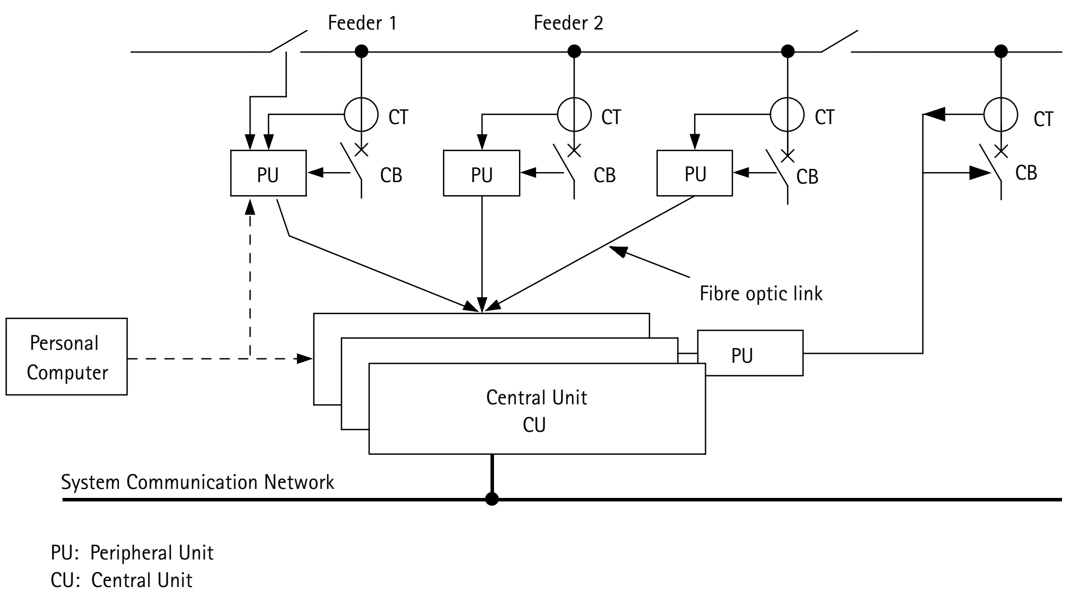


Figure 15.20: Architecture for numerical protection scheme

15.10 NUMERICAL BUSBAR PROTECTION SCHEMES

The application of numerical relay technology to busbar protection has lagged behind that of other protection functions. Static technology is still usual for such schemes, but numerical technology is now readily available. The very latest developments in the technology are included, such as extensive use of a data bus to link the various units involved, and fault tolerance against loss of a particular link by providing multiple communications paths. The development process has been very rigorous, because the requirements for busbar protection in respect of immunity to maloperation are very high.

The philosophy adopted is one of distributed processing of the measured values, as shown in Figure 15.20. Feeders each have their own processing unit, which collects together information on the state of the feeder (currents, voltages, CB and isolator status, etc.) and communicates it over high-speed fibre-optic data links to a central unit. For large substations, more than one central unit may be used, while in the case of small installations, all of the units can be co-located, leading to the appearance of a traditional centralised architecture.

For simple feeders, interface units at a bay may be used with the data transmitted to a single centrally located peripheral unit. The central unit performs the calculations required for the protection functions. Available protection functions are:

a. protection

b. backup overcurrent protection

c. breaker failure

d. dead zone protection

In addition, monitoring functions such as CB and isolator monitoring, disturbance recording and transformer supervision are provided.

Because of the distributed topology used, synchronisation of the measurements taken by the peripheral units is of vital importance. A high stability numerically-controlled oscillator is fitted in each of the central and peripheral units, with time synchronisation between them. In the event of loss of the synchronisation signal, the high stability of the oscillator in the affected feeder unit(s) enables processing of the incoming data to continue without significant errors until synchronisation can be restored.

The peripheral units have responsibility for collecting the required data, such as voltages and currents, and processing it into digital form for onwards transmission to the central unit. Modelling of the CT response is included, to eliminate errors caused by effects such as CT saturation. Disturbance recording for the monitored feeder is implemented, for later download as required. Because each peripheral unit is concerned only with an individual feeder, the protection algorithms must reside in the central unit.

The differential protection algorithm can be much more sophisticated than with earlier technology, due to improvements in processing power. In addition to calculating the sum of the measured currents, the algorithm can also evaluate differences between successive current samples, since a large change above a threshold may indicate a fault – the threshold being chosen such that normal load changes, apart from inrush conditions do not exceed the threshold. The same considerations can also be applied to the phase angles of currents, and incremental changes in them.

One advantage gained from the use of numerical technology is the ability to easily re-configure the protection to cater for changes in configuration of the substation. For example, addition of an extra feeder involves the addition of an extra peripheral unit, the fibre-optic connection to the central unit and entry via the MMI of the new configuration into the central unit. Figure 15.21 illustrates the latest numerical technology employed.

15.10.1 Reliability Considerations

In considering the introduction of numerical busbar protection schemes, users have been concerned with reliability issues such as security and availability. Conventional high impedance schemes have been one of the main protection schemes used for busbar protection. The basic measuring element is simple in concept and has few components. Calculation of stability limits and other setting parameters is straightforward and scheme performance can be predicted without the need for costly testing. Practically, high impedance schemes have proved to be a very reliable form of protection.

Figure 15.21: Busbar protection relay using the latest numerical technology (MiCOM P740 range)

In contrast, modern numerical schemes are more complex with a much greater range of facilities and a much high component count. Based on low impedance bias techniques, and with a greater range of facilities to set, setting calculations can also be more complex.

However, studies of the comparative reliability of conventional high impedance schemes and modern numerical schemes have shown that assessing relative reliability is not quite so simple as it might appear. The numerical scheme has two advantages over its older counterpart:

a. there is a reduction in the number of external components such as switching and other auxiliary relays, many of the functions of which are performed internally within the software algorithms

b. numerical schemes include sophisticated monitoring features which provide alarm facilities if the scheme is faulty. In certain cases, simulation of the scheme functions can be performed on line from the CT inputs through to the tripping outputs and thus scheme functions can be checked on a regular basis to ensure a full operational mode is available at all times

Reliability analyses using fault tree analysis methods have examined issues of dependability (e.g. the ability to operate when required) and security (e.g. the ability not to provide spurious/indiscriminate operation). These analyses have shown that:

a. dependability of numerical schemes is better than conventional high impedance schemes

b. security of numerical and conventional high impedance schemes are comparable

In addition, an important feature of numerical schemes is the in-built monitoring system. This considerably improves the potential availability of numerical schemes compared to conventional schemes as faults within the equipment and its operational state can be detected and alarmed. With the conventional scheme, failure to re-instate the scheme correctly after maintenance may not be detected until the scheme is required to operate. In this situation, its effective availability is zero until it is detected and repaired.

15.11 REFERENCES

15.1 *The Behaviour of Current Transformers subjected to Transient Asymmetric Currents and the Effects on Associated Protective Relays.* J.W. Hodgkiss. CIGRE Paper Number 329, Session 15-25 June 1960.