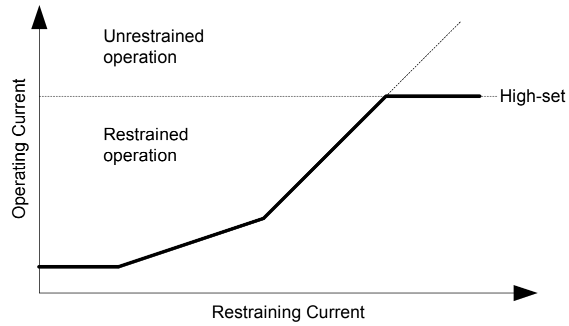

Figure 31 —Differential characteristic with unrestrained mode of operation

7.1.3.4 CT requirements for percentage differential schemes

A compromise is typically made between CTs performance given fault current levels, protection security, and an acceptable sensitivity of the protection.

7.1.4 Advanced bus protection algorithms

Advancements in processing capabilities of modern microprocessor-based bus relays allow new algorithms with improved speed of operation and immunity to errors caused by saturated CTs.

High sampling rates, low latencies when processing the data, and optimized filtering algorithms result in fast relay operation.

Algorithms referred to as *CT saturation detectors* are often deployed to improve security of relay operation.

7.1.4.1 Current transformer saturation detection

One known approach to the CT saturation problem is to detect an external fault before any of the CTs saturates. This group of methods takes advantage of the observation that any CT performs adequately at least for a short period of time, even if it saturates severely later into the fault. During the initial phase of an external fault, the differential current remains low while the restraining current increases quickly. Depicting this on the operating/restraining current plane, one notices that the trajectory initially moves rapidly to the right without entering the differential operating characteristic (time period from t_0 to t_1 in Figure 32). Even with considerably underrated CTs this situation lasts for some time (fraction of a cycle) and can be reliably detected by fast-sampling modern microprocessor-based relays.

Subsequent to the short period of error-free CT operation, saturation may occur reducing the secondary current, and therefore reducing the amount of the restraint (trajectory moves to the left), while increasing the spurious operating signal (trajectory moves upward). This may result in false operation of a percentage-restrained differential function (time period t_1 to t_2 in Figure 32).

On the other hand, during internal faults the trajectory moves upward from the very beginning without the distinctive shift to the right (time period t_0 to t_3 in Figure 32). It may then move down and to the left as CT(s) saturate, possibly exiting the operate region.

Tracking the operating/restraining trajectory allows the algorithm to distinguish external from internal faults. Rapid measurement is required for this purpose as the period of correct CT performance (t_0 to t_1) may be short.

Some implementations of this method incorporate a time derivative of the restraining current. This can be summarized as follows: an external fault is detected if the operating current remains low while the restraining current is already high or it is increasing very rapidly.

Other versions of this principle may use a ratio of the rates of change of the operating and restraining currents.

Regardless of the details of implementation, this group of methods detects external faults in a transient manner. This requires a separate mechanism to latch and reset the transiently established "external fault detected" flag. The latching logic needs to be refined to cope with evolving external-to-internal faults.

Some algorithms use a phase angle difference between the derivative of the instantaneous restraining current and the derivative of the instantaneous operating current, to differentiate between external and internal faults. For an external fault, the derivative of the operating current always lags the derivative of the restraining current, and for an internal fault, the two derivatives are practically in phase.

Implementations of the aforementioned principles are capable of detecting external faults in as quickly as 0.15 of a power cycle as long as the CTs operate with only minor errors during that period. Such performance practically eliminates the need to use very high quality CTs for low-impedance differential relaying, or to perform involved engineering calculations to set the relays.

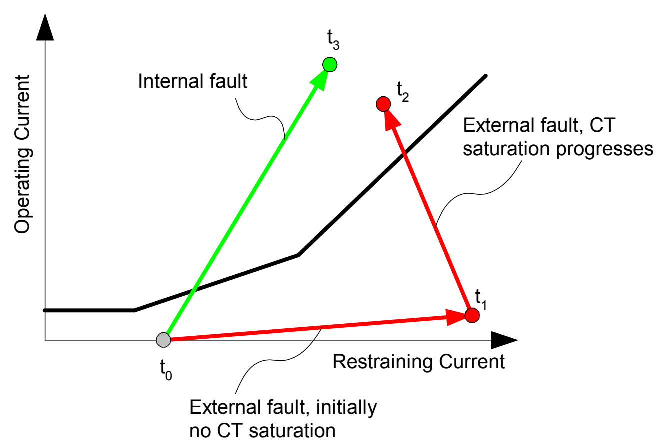

Figure 32—Difference in trajectories of internal and external faults

7.1.4.2 Directional principle

Some relays apply a directional principle for stability during external faults. Figure 33 shows sample waveforms of the ratio and secondary currents of a CT carrying an external fault current away from the bus. The rest of the bus currents sum up exactly to the amount of the ratio current, and this sum flows in the opposite direction.

This observation allows applying a directional check to confirm if the elevated operating current of a percentage-restrained differential protection function is caused by an internal fault or external fault combined with saturated CTs.

Under internal faults all significant currents flow approximately in the same direction. Only relatively minor differences occur due to phase differences in the equivalent electromotive source, and/or different angles of the equivalent source impedances.

Under external faults, the current in a faulted circuit is out of phase with the sum of all the other currents, or with all the other significant currents. Saturation of a CT affects the phase angle of its secondary current much less than the secondary current magnitude. Therefore, using the phase information alone in an extra directional check improves security of the plain percentage-restrained differential function.

The phase check can be performed in the time domain as shown in Figure 33(b), or in the frequency domain as in Figure 33(c).

When implemented in the time domain (phase comparison principle), the algorithm checks polarities of the major currents against each other. The dc components are typically filtered out in order to make the implementation work.

When implemented in the frequency domain (directional principle), the algorithm checks relative direction of the phasors of the major currents.

Only the major currents are typically included in the directionality check. There is a danger that during internal faults small currents may flow out of the bus feeding loads, or circulate out and back inside the differential zone of protection. Checking directionality of such currents would jeopardize dependability of the algorithm. Either a user adjustable setting is provided to indicate the level above which the current direction is checked, or the algorithm selects the currents autonomously based on their relative magnitudes and their relations to CT rating currents.

Typically, 75º to 90º coincidence limit angles are applied.

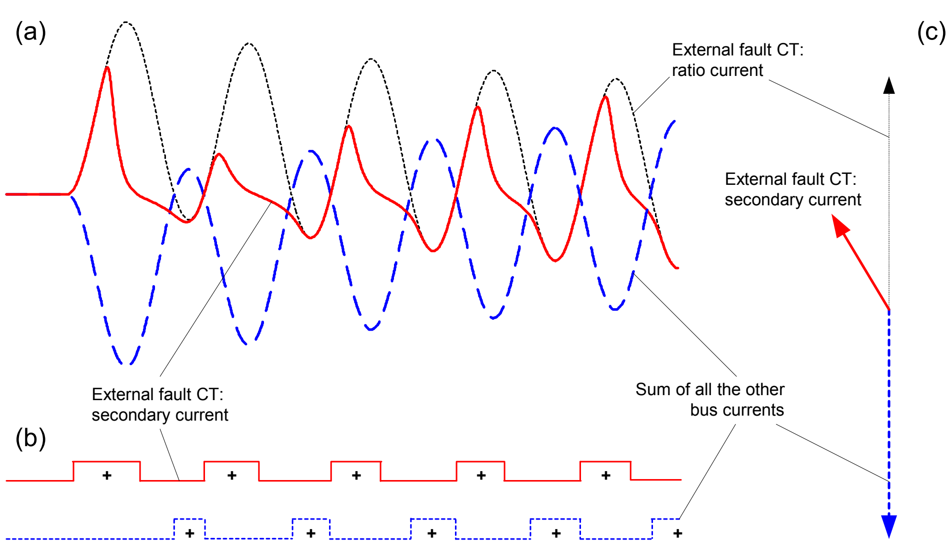

Figure 33—External fault with CT saturation: current waveforms (a), phase comparison check (b), phasor directional check (c)

7.1.4.3 Combined differential and directional principle

One solution combines the differential and directional principles into a single algorithm. In this approach in addition to an instantaneous differential current, instantaneous currents flowing in and out of the zone are calculated. All zone currents having positive polarities at a given time are added and form the incoming current. All zone currents of negative polarities at a given time are added and form the outgoing current. In this way protection of a bus of any size is reduced to analysis of three signals: the differential, incoming, and outgoing currents.

The instantaneous values of the three signals are converted into magnitudes as per the art of numerical protection. Simple operating logic is derived from the consistent relationships between magnitudes of the three basic signals under various conditions.

7.1.4.4 Operating logic

Operating logic of an advanced low-impedance differential function may involve a differentially connected overcurrent function, a percentage-restrained differential function, a directional check, a CT saturation detection algorithm, a level check for the differential and restraining currents, and other conditions.

Specific solutions balancing security and dependability differ between various relays and may include: operation on the 2-out-of-2 basis (differential and directional); automatic and temporary increase of the slope upon detecting external faults; automatic switching to the 2-out-of-2 principle upon detecting CT saturation; and other solutions.

Often, the operating logic can be customized via the user programmable logic engine of the relay.

7.1.4.5 CT requirements for advanced low-impedance bus differential relays

As previously discussed in this clause, advanced numerical low-impedance bus differential schemes with high sampling rates and capability of quickly detecting external faults and CT saturation, are more forgiving of the performance and application of CTs than other bus relaying schemes. In particular it is permissible to have CTs of different accuracy classes and ratios connected to microprocessor-based low-impedance bus differential relays. Typically, modern schemes allow for quite severe saturation of CTs without jeopardizing security of the application. When applying proprietary algorithms for enhanced security under CT saturation, advanced low-impedance relays require that manufacturer recommendations—typically related to the time to CT saturation under external faults—be followed.

Quite often, the schemes require time to saturation to be above a certain minimum value such as 0.15 to 0.25 of a cycle. Saturation occurring after this minimum required time is handled correctly regardless of the amount of saturation that follows. The time to saturation can be easily calculated based on known engineering practices that take into account CT saturation voltage, total burden, expected X/R ratio, and highest expected residual flux (refer to IEEE Std C37.110). The latter can be assumed as high as 80% of the saturation level.

Sound engineering practice needs to be applied in selecting CTs, regardless of the protection scheme used. However, advanced microprocessor-based bus differential relays simplify engineering effort with respect to CT selection/analysis and setting calculations.

7.1.5 Differential methods with linear couplers

Bus differential protection with linear couplers is conceptually simple. An accurate measure of the current unbalance is achieved by connecting the outputs of linear couplers in series for all the circuits bounding a protection zone (Figure 34). The resultant voltage is accurate due to the saturation-free operation of the linear couplers. Even though each individual linear coupler amplifies high-frequency current components in the output voltage, the differential voltage is not affected as all frequency components balance to zero unless there is a fault in the zone. A simple low-energy voltage relay is typically used to detect internal bus faults. It is a common practice to follow manufacturer recommendations regarding pickup settings, burden requirements, voltage withstand, and other practical considerations.

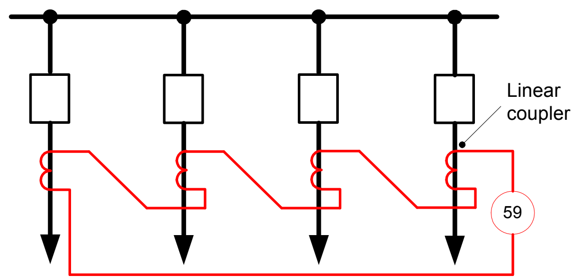

Figure 34—Bus protection with linear couplers

Differential protection with linear couplers shares some characteristics with high-impedance protection. Both methods require dedicated instrument transformers, both assume identical transformation ratios, and both are not naturally suited for reconfigurable buses.

This guide does not consider linear coupler applications in detail. A number of schemes using linear couplers have been deployed in the past, remain operational, and are being refurbished as required, but practically no new installations are being added.

7.1.6 Differential methods with Rogowski coils

Rogowski coils, like linear couplers, have windings wound over an air core and therefore are immune to problems of core saturation. Their output signal is a low-level voltage proportional to the time derivative of the primary current. As such they can be used in differential protection methods, similarly to linear couplers.

Rogowski coils are lightweight, compact, and may be designed so that the same coil satisfies both protection and metering accuracy requirements. As their output is a low energy signal, they require careful shielding and grounding of their secondary circuitries, and relays capable of accepting the current signals as low-level voltage inputs. IEEE Std C37.235™-2007 [B19] provides guidelines for the application of Rogowski coils in power system protection. Rogowski coils are better suited to indoor switchgear bus protection applications that employ relatively short secondary lead lengths, than they are to outdoor substation bus protection applications that require long secondary lead lengths with greater exposure to interfering signals.

When applied to bus protection, the coils can be connected into a differential scheme as shown in Figure 35(a). In this application all Rogowski coils are of equal ratio, interconnected in series, and connected to a voltage relay on a per phase basis. The pickup setting needs to account for finite measuring accuracy of the applied coils and the voltage relay during external faults, as well as fulfill dependability requirements for internal bus faults. This scheme is similar to differentially connected overcurrent schemes with the exception that CT saturation is not a problem.

In an alternate application, similar to the percentage-restrained method, all Rogowski coils are individually connected to a multi-input relay and the differential signal is derived internally [Figure 35(b)]. Percentage restraint can be used to deal with unbalance signals during external faults caused by the finite measuring accuracy of the coils and relay. This scheme allows internal ratio matching between the coils, facilitates protection of reconfigurable buses through dynamic bus replica, and allows for built-in backup and BF functions by measuring all individual currents of the bus.

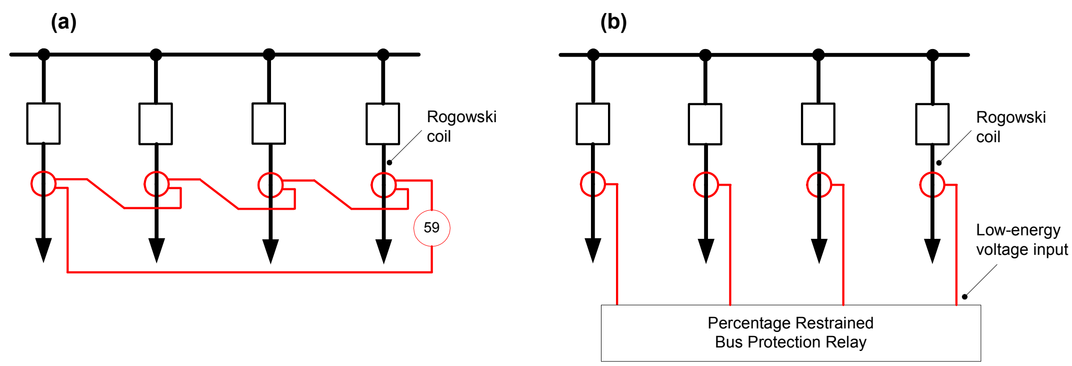

Figure 35—Bus protection with Rogowski coils: differentially connected coils (a), all coils connected to a bus relay with the differential signal derived internally (b)

7.2 Zone-interlocked schemes

Dedicated instantaneous bus protection is regarded as essential for higher system voltages. Traditionally, however, distribution system bus faults have been cleared by time-delayed protection upstream. Microprocessor-based multi-function relays now allow proven schemes to be applied to protect distribution system buses.

The bus protection is achieved largely using network element relays required for their primary task of network element protection. The advantages offered by such zone-interlocked schemes include the following:

— Faster bus fault clearance compared to tripping initiated by time-delayed differentially connected overcurrent or time-coordinated partial differential overcurrent protection.

— Bus protection without the need to install a dedicated bus relay and CTs—the zone-interlocked scheme uses protection elements and CTs already associated with the network element protection relays.

— Fault and disturbance records are stored in network element relays for bus faults, allowing better fault analysis.

— Zone-interlocked schemes can be easily modified to suit substation extension.

7.2.1 Simple zone-interlocked schemes

Figure 36 shows a typical distribution substation layout, where one source feeder (incomer) supplies a number of outgoing radial feeders from a single bus.

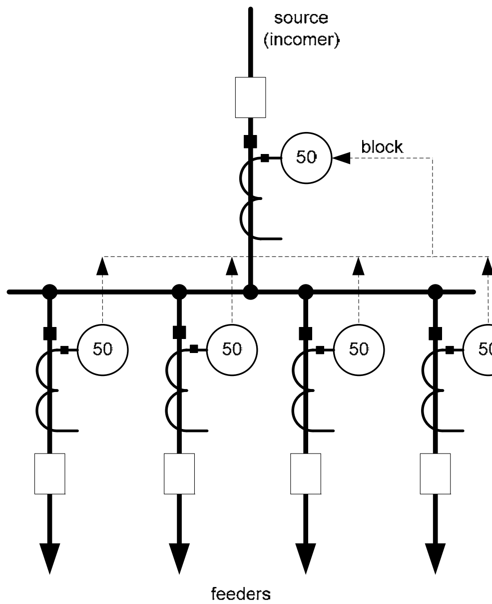

Figure 36—Simple blocking scheme for a single bus with a single source

The feeder protection systems are equipped with an instantaneous element that on detection of a feeder fault sends a blocking signal to the bus protection. In Figure 36 this element is labeled as an instantaneous overcurrent type (50), but as described below, other types are required in some situations.

The bus protection measuring element is also shown here as an instantaneous overcurrent and also may need to be another type in some situations. It too may be integrated in a network element protection. The bus protection measuring element is unable on its own to distinguish between a bus fault and a feeder fault. However, for a feeder fault, the feeder protection blocks bus tripping. For a bus fault, no blocking action occurs and the bus trips after only a short coordination delay.

Simple blocking schemes may also be used where there are multiple sources feeding the bus. In that case, the bus protection measuring element is essentially a partial differential scheme, measuring only the sum of the source currents. Simple blocking schemes may also be used on some switchable (reconfigurable) bus arrangements. Dynamic bus replica logic is used to switch the blocking signals as required by the present bus configuration.

The bus blocking signal may be implemented using programmable contact outputs of the feeder relays connected in parallel, driving a programmable contact input of the relay containing the bus protection measuring element. In stations with an Ethernet local area network (LAN) connecting the relays for SCADA and/or engineering access, the bus blocking signal may also be communicated over this same LAN or other peer-to-peer protection grade communication network.

Usual coordination rules apply. The bus protection measuring element is set sensitive enough to pick up on all bus faults. The outgoing feeder relays are set to pick up on all external faults that could activate the bus protection measuring element. A short-time coordination delay is required in the bus protection to allow the blocking signal to be reliably established and delivered before bus tripping occurs.

Ground fault elements in particular are coordinated considering that loads can be grounded and could back-feed a zero-sequence current to bus faults with ground. If proper pickup current coordination is not possible, a directional ground element (67N) may be required on some of the outgoing feeders. A similar problem can exist with phase faults where the feeder contains distributed generation or a large synchronous motor component.

This simple concept can be extended to include BF protection. Both time-coordinated bus protection and simple blocking bus protection can be provided in one package for extra dependability.

7.2.2 Directional blocking scheme

For simple buses with a single source and a predetermined short-circuit current flow zone-interlocked schemes can be implemented with non-directional overcurrent relays. More complex bus arrangements, with multiple sources and several patterns of short-circuit current flows, require directional relays.

Figure 37 shows a typical substation layout with two sources (S1 and S2) feeding a number of outgoing radial feeders from a two-section bus (Bus 1 and Bus 2) with a tie breaker (TB). An overcurrent relay is installed at the tie breaker.

In order to facilitate a bus protection blocking scheme the tie breaker relay is directional to detect through fault conditions. Relays on the outgoing feeders and the sources can be non-directional. Alternatively, the source CT and the tie breaker CT can be connected as a partial differential to the source relay. With this approach, a CT is required on each side of the tie breaker for overlapping zones, but no additional relay is required on the tie breaker and all relays can be non-directional.

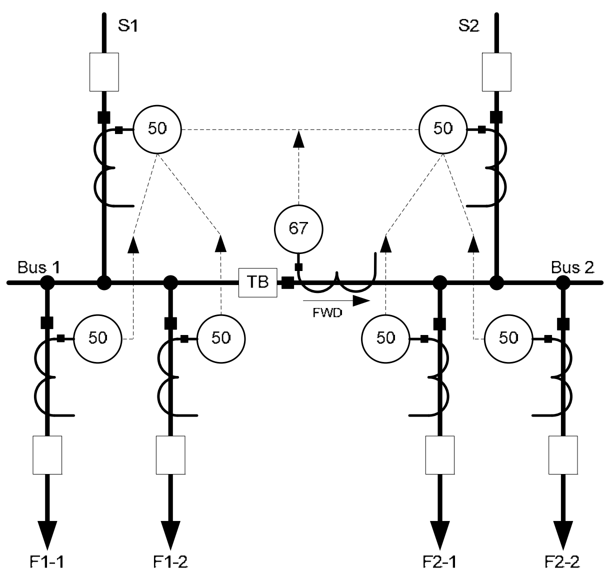

Figure 37—Bus blocking scheme for a dual-source, sectionalized bus

Assume a forward direction for the tie breaker relay for current flows from Bus 1 to Bus 2. Under such conditions trip logic of Figure 38 applies.

Asymmetry at the tie breaker makes the trip logic different for Bus 1 and 2. Note that the trip logic for both buses is of a blocking type. Inactivity of all outgoing feeder relays and the tie breaker relay with the source relay picked up would result in tripping. This means a failure of a blocking relay will result in tripping the bus for an external fault on the corresponding feeder. This is acceptable as a backup trip for downstream faults under the failure of one of the outgoing feeder relays, but it is desirable to avoid false tripping for upstream faults if the tie breaker relay fails. Applying directional relays at the sources solves this problem. Referring to logic of Figure 38, the S1 PKP signal is replaced by S1 REV (assuming forward direction away from the bus), and S2 PKP by S2.

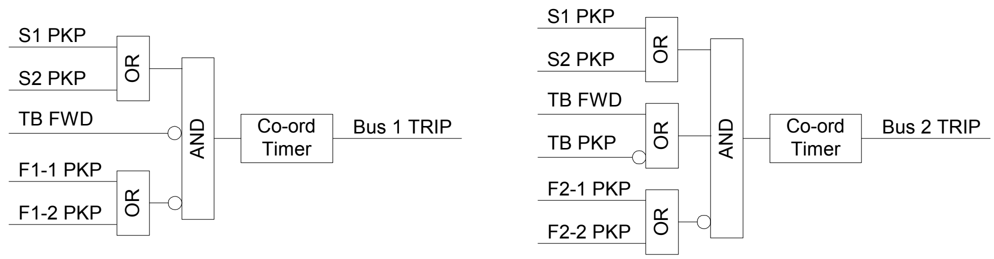

Figure 38—Trip logic for application of Figure 37 (PKP = non-directional overcurrent condition, FWD = forward direction, REV = reverse direction)

Outgoing feeders could use non-directional relays if all feeders are radial, however directional relays can be used when voltage or power measurement functions are required, or merely for standardization of the application.

The use of directional overcurrent relays would also allow bus blocking schemes where outgoing feeds are not radial (e.g., paralleled or forming part of a ring main). Engineering of such applications is, however, more complex. First, detailed short-circuit studies may be required to determine proper coordination of the pickup levels among all the relays. Second, current flow patterns are examined to decide which relays need to be directional. If possible, all elements used for bus blocking schemes may be selected to be directional eliminating the latter problem.

Positions of CTs define boundaries of zones of protection. Normally, feeder zones commence on the bus side of the breakers, while the bus zone terminates on the line side of the breakers. Bus blocking schemes violate this principle and do not allow for zones overlapping. Feeder application typically takes precedence, and the bus-side CTs are used in the bus blocking schemes.

Also, blocking schemes provide for near instantaneous but still slightly delayed fault clearing times. Therefore, for applications demanding high performance of bus protection, differential schemes are recommended for speed and selectivity.

7.2.3 CT requirements for bus blocking schemes

Blocking schemes are relatively immune to CT errors, including saturation. Given applied relay settings, CTs need to be rated to satisfy the following three requirements:

a) Tripping functions, that is overcurrent elements required to pick up on bus faults and trip the bus unless blocked, are required to be dependable for all internal faults given the assumed sensitivity objectives. Typically, pickup levels are set above full load to prevent the scheme from being armed permanently, but below the minimum bus fault current. Normally, the setting is relatively low and the scheme faces no dependability problems even under severe saturation of CTs. In cases of very high fault currents and low-ratio CTs such as in medium voltage industrial grids, special attention is required (see Linders et al. [B22]). The amount of secondary current may be considerably reduced due to severe CT saturation jeopardizing dependability of the tripping or blocking overcurrent functions.

b) Blocking functions, that is overcurrent elements required to pick up on external faults to block the tripping functions, are required to be dependable for all external faults for which the tripping functions pick up. Severe saturation may reduce the apparent secondary current seen by the relay and jeopardize security of the scheme. This again may be a problem if very low-ratio CTs are used. Typically, the tripping function is fed from a large ratio CT and does not have problems picking up on external faults, while the blocking function fed from a low-ratio CT may fail to pickup, or pickup late after the coordination timer expires, leading to inadvertent operation of the scheme.

c) Directional functions, if used, are required to retain directionality under CT errors. The fundamental frequency component in a secondary current could shift due to CT saturation. Various implementations of directional functions could respond differently to saturated waveforms. In particular, negative-sequence or neutral overcurrent directional functions need to be considered carefully under CT saturation.

Typically, all three requirements: dependability of the tripping functions on bus faults, dependability of the blocking functions on external faults, and directional integrity, are satisfied even under considerable CT saturation imposing no extra requirements for the CT. Typically, CTs properly rated for protection of circuits originating at the bus are sufficient for deployment of the bus blocking scheme.

More stringent CT requirements apply if a given blocking scheme is not based on phase overcurrent functions, but on neutral or negative-sequence functions. These derived signals exhibit much higher sensitivity to faults and allow protecting buses in impedance grounded systems and/or under very weak infeed conditions. However, CT errors can cause relays to measure spurious neutral and negative-sequence currents jeopardizing security of such schemes. Various restraining techniques or time delay are used in those applications.

7.3 Fault bus schemes

In metal-clad switchgear and in some outdoor installations the fault bus system for the detection of ground faults can be used. This scheme requires isolating the bus support structure from ground and grounding this structure through a single-point ground and CT as in Figure 39. An overcurrent relay connected to this fault bus CT initiates a trip to all the breakers required to isolate the bus. The maximum effectiveness is obtained by this method when the switchgear is of the isolated phase construction. In this case the faults will always involve ground. Phase-to-phase and three-phase bus faults not involving ground cannot be detected by a fault bus scheme.

For large switchgear, it may be desirable to ground the structure at more than one point, each through a CT. The secondaries of all these CTs are paralleled to the single overcurrent relay. If paralleled, the grounding CTs need to be of the same ratio in order to make the scheme immune to external faults causing circulating ground currents. Since fault currents do not flow in this fault bus CT except for bus ground faults, the protection system can be made very sensitive.

The selectivity of this scheme is imperfect as its measuring zone includes the part of connected power cables enclosed by the switchgear, a zone of overlap with network element protection. False tripping can also occur for faults on auxiliary power systems used for mechanism spring charging motors, cubicle lights, etc. This can be avoided by bringing the auxiliary supply into the switchgear through the ground fault CT so that normal auxiliary system ground faults are self-canceling. By using this supply arrangement to feed switchgear receptacles, nuisance trips from power tools can also be avoided. The trip circuit may be supervised by a relay in the neutral or the station's ground relay current polarizing circuit to prevent false tripping from the accidental grounding of power tools, etc. Where unsupervised or where there is an overlap in the protected zone, a coordinating time delay is recommended.

The fault bus system is applicable to new installations where provision can be made for effective isolation from ground. Certain existing installations may not be adaptable due to alternate paths for ground fault current in concrete reinforcing rods or structural steel.

It is necessary to insulate cable sheaths from the switchgear enclosure. An external flashover on a cable entrance bushing may cause improper operation unless the bushing support is insulated from the structure and independently grounded.

It is important to note that the bus structure insulation system is carefully maintained. A dirty or contaminated insulator will allow ground fault current to bypass the fault bus CT, compromising the