Reliable Busbar and Breaker Failure Protection With Advanced Zone Selection

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RELIABLE BUSBAR AND BREAKER FAILURE PROTECTION WITH ADVANCED ZONE SELECTION

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ABSTRACT

Busbar protection has always been important, but high-speed schemes are now more necessary than ever because many power systems are operated close to their stability limits. For this reason, busbar and breaker failure protection schemes that require time coordination such as that provided by Zone 2 distance and overcurrent relays are no longer acceptable. Modern numerical relays use innovative algorithms to fulfill busbar protection requirements of fast operating times for all busbar faults, security for external faults with heavy CT saturation, and minimum delay for evolving faults.

This paper describes a reliable substation protection system that involves busbar protection, station-wide breaker failure protection, and advanced zone selection. This protection system is suitable for application over a wide range of diverse protection philosophies. The paper suggests a unique combination of multiple protection principles and discusses the integration of station-wide busbar and breaker failure protection in one relay.

In this paper, we explain an implementation of advanced zone selection and then present innovative busbar protection and station-wide breaker failure protection algorithms. We also provide diverse application philosophies, tie-breaker considerations, end-zone protection, and backup overcurrent protection. Finally, test results show the fast response of the relay for busbar faults, security for external faults, and minimum delay for evolving faults.

INTRODUCTION

Traditionally, two separate devices provide busbar and breaker failure protection [1]. This device separation results in additional wiring and duplication of common functionality. For example, busbar protection uses disconnect status from each terminal to assign the proper currents to the differential element and to determine which terminals to trip for busbar faults. Breaker failure protection uses the same information to determine which breakers to trip for breaker failure conditions.

Integrated busbar and breaker failure protection eliminates duplication of common functionality, minimizes wiring, and simplifies protection scheme design. Narayan and Brulhart [2] described a method of breaker failure protection with busbar protection implemented in analog electronic relays. For detecting a breaker failure condition, instead of using an overcurrent relay, the method extends the zone of busbar protection to include the zone of the faulty breaker. The proposed scheme uses an image of the bus sections corresponding to the actual operating conditions. When breaker failure occurs, the relay trips all breakers supplying the fault current connected to the same busbars as the faulty breaker.

For microprocessor-based digital busbar protection, it is common to integrate many busbar protection functions into the same relay. Peck, Nygaad, and Wadelius [3] introduced breaker failure protection integrated as an option for each terminal in a distributed architecture. Each terminal unit contains a three-phase overcurrent element with fast pickup, reset, and two timers. Separate binary inputs on each terminal unit provide breaker failure initiation from an external protection device. In another method that is commonly employed in Germany, Kumar and Hansen [4] and Funk and Ziegler [5] described how to realize breaker failure protection by unbalancing bus differential protection after a time delay. If a terminal protection tripping condition persists for longer than the set breaker failure time, the relay reverses the current of the associated terminal in the bus differential calculation. This current reversal effectively changes the fault from external to internal, resulting in busbar protection operation.

Busbar protection traditionally comes in many forms [1], and [6]–[10]. Among these are frame leakage, high-impedance relays, medium-impedance relays, low-impedance distributed systems, and low-impedance centralized units, based upon electromechanical, electronic (solid state), and microprocessor technologies [11]–[17]. In general, amplitude comparators (differential elements) and phase comparators (directional elements) provide the measurements necessary for busbar protection.

Percentage restraint differential protective relays have been in service for many years [18]. Differential relays perform well for external faults as long as CTs reproduce the primary current correctly. When a CT saturates, the secondary CT currents do not sum to zero, and differential current appears in the differential relay. If the ratio of this differential (operating) current to the restraining current is greater than the slope setting threshold, the differential relay may declare an internal fault condition and misoperate. Several solutions to the CT saturation problem have been proposed in the past. Kennedy and Hayward [19] proposed the use of harmonics to prevent differential relay misoperations resulting from CT saturation. They called this the principle of harmonic current restraint because, "It takes advantage of the difference in wave form between the differential current caused by current transformer saturation or magnetizing inrush currents to restrain the relay from operating except when a fault exists within the protected zone." Sharp and Glassburn [20] proposed using a differential relay with a variable percentage characteristic to prevent misoperations when one or more CTs saturate during external fault conditions. Different devices around the world have for many years used the solutions Kennedy, Hayward, Sharp, and Glassburn proposed. These solutions provide proper differential element operation in most cases [11], [21], and [22] by blocking the trip signal for a fixed time after detection of an external fault condition. However, one would not want to use the block method for faults that evolve from external faults to internal faults, because of the fixed time delay in tripping.

Current directional relays take advantage of phase angle information to provide fault direction. This method is based on the fact that CTs provide adequate phase angle information even during CT saturation conditions. Haug and Forster [11] combined differential and directional elements to provide power system apparatus protection. In this approach, the directional element supervises the differential element at all times. Unfortunately, this scheme is less effective in detecting high-resistance faults when load current, flowing away from the faulted protection zone during the busbar fault, desensitizes the relay.

Busbar protection philosophy traditionally calls for two-out-of-two trip criteria, where two separate measuring elements must agree before protection issues a trip signal. Realization of the two-out-of-two trip criteria can occur through one of two combinations:

- Dual differential element combination (main zone and check zone) [5]
- Differential element and directional element combination (main zone and directional element) [11]

Each combination has an advantage over the other; the weakness of one is the strength of the other. In particular, differential elements are more vulnerable to CT saturation than are directional elements, but directional elements are more vulnerable to high-impedance faults.

In a substation, CT saturation can occur because of large fault currents, poor CT selection, or possible remanent flux from switching operations. A high-impedance fault can occur in cases of arc resistance, impedance grounding, or deterioration of system grounding. CT saturation is a concern in networks with high fault currents and low CT ratios. In networks with impedance grounding, all ground faults are high-impedance faults. Although relays may have been correctly selected in the initial network design, changes in the network can adversely influence the network parameters. For example, network extensions or reduced source impedance result in higher fault current, and deterioration of the substation grounding mat can result in higher fault impedance for ground faults.

Modern busbar protection relays should not only include protection elements to allow for diverse network parameters, but the implementation of these elements in the relays must ensure continual, uncompromising relay performance, despite changes in network parameters. In general, busbar protection must comply with the following performance requirements [23]:

- Fast operating times for all busbar faults
- Security for external faults with heavy CT saturation
- Minimum delay for evolving faults (external to internal fault)

Furthermore, the continuing drive for substation automation includes electrically operated disconnects to connect terminals to busbars. Depending on the particular busbar protection, disconnect operation may require disabling of the busbar protection during the switching operation to avoid relay misoperation resulting from incorrect terminal current-to-differential element assignment. Zone selection provides a way to replicate the station disconnect status by using the disconnect auxiliary contacts; there is no need to disable busbar protection. Figure 1 shows the overall block diagram of a protection system that integrates busbar protection, breaker failure, and zone selection.

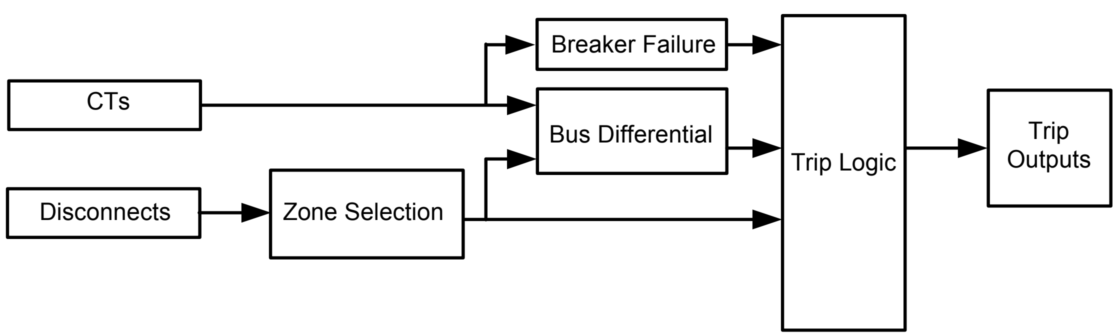


Figure 1 Block Diagram of the Protection System

PROTECTION ZONE SELECTION

In power system networks, a busbar is a connection point for many generation, transmission, or load circuits. If a fault occurs on a busbar, all circuits supplying fault current must trip to isolate the fault. A busbar fault can result in considerable loss of service and severe system disturbance. As a result of improved continuity of energy supplies and flexibility of system operations, some power system stations use complex bus arrangements that increase demands for sophisticated bus protection schemes [16]. One key component of a sophisticated bus protection scheme is zone selection, particularly dynamic zone selection. Dynamic zone selection automatically assigns terminal current to the appropriate differential element, without the need to disable the busbar protection during the switching operation.

Zone selection information applies to both busbar and station-wide breaker failure protection, i.e., using this information, the relay determines the circuit breakers that will trip in the event of a busbar fault or a breaker failure condition. We applied graph theory in the implementation of dynamic zone selection. Details on graphical representation of bus arrangements, graph operations, and associated matrix operations are described in [24] and [25].

To illustrate an implementation of zone selection in relays, we use a hypothetical bus arrangement as shown in Figure 2. There are four bus-zones (BUS1, BUS2, BUS3, BUS4) and eight terminals (TM1, TM2, …, TM8). We define a protection zone as an area of protection formed by a minimum of one bus-zone. To distinguish between a protection zone and a bus-zone, we also include zone names (Protection Zone 1 through Protection Zone 4) for the respective busbars. A protection zone can include more than one bus-zone. Merging two bus-zones results in a single protection zone. When no bus-zones are merged, a protection zone and a bus-zone have the same meaning. We have three disconnect switches (only disconnects linking busbars are shown): DS1 linking BUS1 and BUS3, DS2 linking BUS1 and BUS2, and DS3 linking BUS3 and BUS4. When DS1 is closed while DS2 and DS3 are open, BUS1 and BUS3 are merged into a single zone; BUS2 will form a zone by itself, and BUS4 will form another zone for differential protection. (DS1 closed represents a state in which BUS1 and BUS3 are solidly connected.)

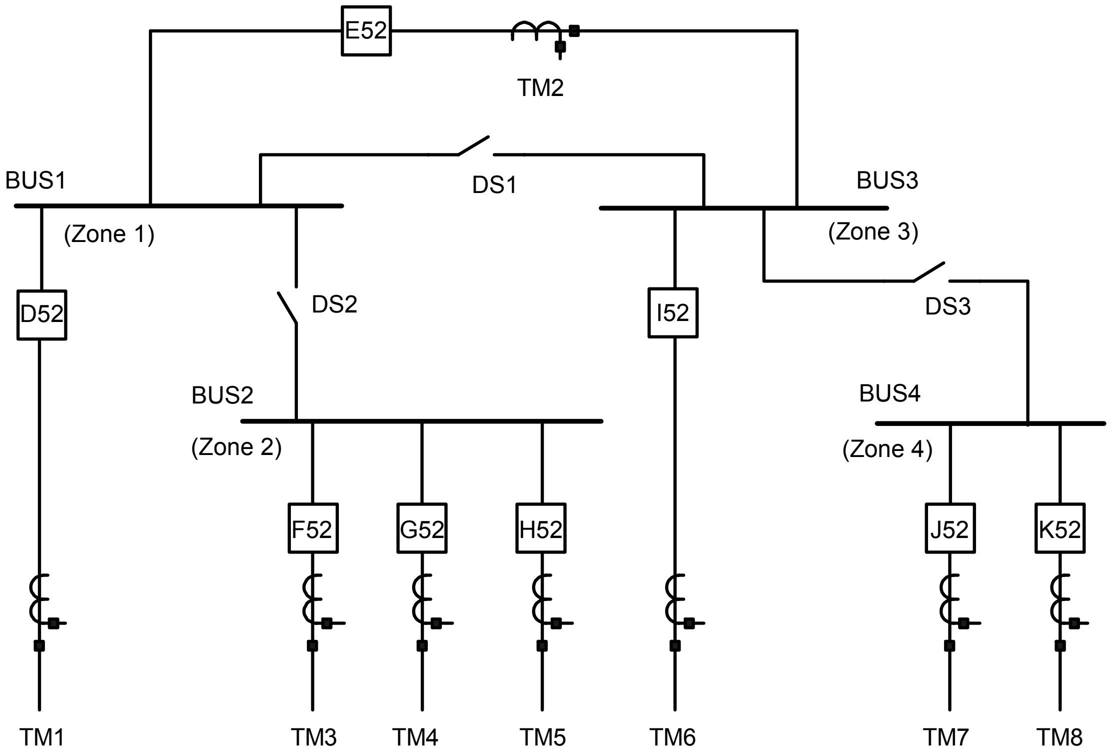
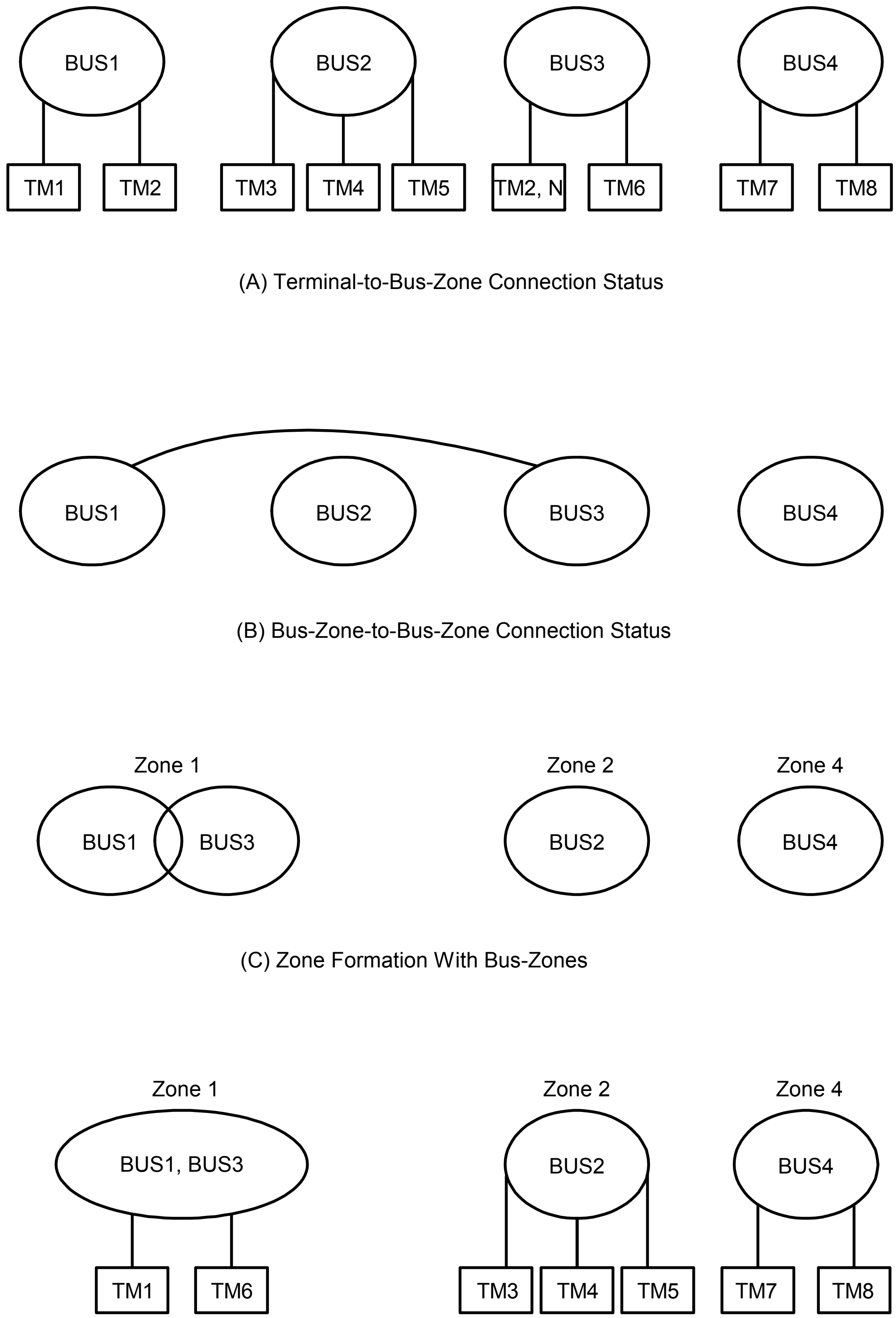


Figure 2 Illustration of a Bus Arrangement With Four Buses and Eight Terminals

For this bus arrangement, the input data for zone configuration include terminal-to-bus-zone connection programmable equations I[q]BZ[p] and bus-zone-to-bus-zone connection programmable equations BZ[p]BZ[p]. For these equations, q (terminals) = 1,2,…,8, and p (buses) = 1,2,…,4.

Once the relay has the connection information, it can select the protection zone by using the algorithm shown in Figure 3 (A) through Figure 3 (D). Figure 3 (A) represents a graphical description of the simplified bus arrangement shown in Figure 2.



(D) Zone Formation With Terminals

Figure 3 Graphical Description of a Four Bus-Zone, Eight-Terminal System

From the terminal-to-bus-zone information I[q]BZ[p], we can construct the terminal-to-bus-zone connection matrix as shown in Table 1.

Table 1 Terminal-to-Bus-Zone Connection Matrix

	BUS1	BUS2	BUS3	BUS4
TM1	1	0	0	0
TM2	1,P	0	1,N	0
TM3	0	1	0	0
TM4	0	1	0	0
TM5	0	1	0	0
TM6	0	0	1	0
TM7	0	0	0	1
TM8	0	0	0	1

Note that Terminal 2 (TM2) has two entries: an entry in BUS1 as well as an entry in BUS3. This is because Terminal 2 (TM2) is a bus-coupler that links BUS1 and BUS3. The relay uses only one CT input for both BUS1 and BUS2, the appropriate polarity indicated by P (positive) and N (negative).

From the bus-zone-to-bus-zone connection programmable equations BZ[p]BZ[p], we construct the bus-zone-to-bus-zone connection matrix BZ[p]BZ[p] similarly to the terminal-to-bus-zone connection matrix. Figure 3 (A) shows all three disconnects (DS1, DS2, and DS3) open. Closing disconnect DS1 merges BUS1 and BUS3. Figure 3 (B) shows this condition, and Table 2 shows the bus-zone-to-bus-zone connection matrix for the combination (DS1 closed, DS2 and DS3 open).

Table 2 Bus-Zone-to-Bus-Zone Connection Matrix When Merging BUS1 and BUS3

	BUS1	BUS2	BUS3	BUS4
BUS1		0	1	0
BUS2			0	0
BUS3				0
BUS4				

Based on the information of the matrix BZ[p]BZ[p], we identify the group of connected bus-zones by determining the interconnections between bus-zones.

In Figure 3 (C), Protection Zone 1 covers the group that consists of BUS1 and BUS3. Protection Zone 2 covers BUS2, and Protection Zone 4 covers BUS4. In this case, Protection Zone 3 contains no terminals because BUS3 is already included in Protection Zone 1. Table 3 shows the matrix relating the protection zones and busbars after BUS1 and BUS3 merge.

Table 3 Protection Zone and Busbar Relationships After BUS1 and BUS3 Merge

	BUS1	BUS2	BUS3	BUS4
Protection Zone 1	1	0	1	0
Protection Zone 2	0	1	0	0
Protection Zone 3	0	0	0	0
Protection Zone 4	0	0	0	1

If a terminal is a bus-coupler that is part of the two merged bus-zones, this terminal disappears from the protection zone, as shown in Figure 3 (D). The protection zone and terminal matrix is as shown in Table 4. Note that TM2 is absent from the matrix because it is a bus-coupler.

Table 4 Protection Zone and Terminal Relationships After BUS1 and BUS3 Merge

	TM1	TM2	TM3	TM4	TM5	TM6	TM7	TM8
Protection Zone 1	1	0	0	0	0	1	0	0
Protection Zone 2	0	0	1	1	1	0	0	0
Protection Zone 3	0	0	0	0	0	0	0	0
Protection Zone 4	0	0	0	0	0	0	1	1

Note that disconnect and breaker auxiliary contacts typically provide station configuration information through control inputs in the form of programmable equations. By evaluating these programmable equations, the zone-selection logic assigns the currents to the appropriate differential elements. When disconnects are closed in such a way that a solid connection exists between two (or more) zones, the zones merge, and only one zone is active. The active zone after a merge is always the zone with the lower number. For example, if BUS1 and BUS3 merge, Protection Zone 1 encompasses Protection Zone 3.

When the programmable equation representing a terminal-to-bus-zone connection becomes a logical 1, the zone-selection algorithm processes the current values associated with that particular terminal. When the equation is logical 0, the current values are neither processed nor considered in the differential calculations. This is also true for the trip output. When the programmable equation of a terminal is a logical 0, the differential element issues no trip signals to that terminal.

Based on the programmable equations I[q]BZ[p] and BZ[p]BZ[p], the zone-selection logic determines the following:

- The bus-zone(s) to be included in each protection zone
- The terminals to be included in each protection zone
- The terminals to trip for differential and breaker failure protection operations

BUSBAR DIFFERENTIAL PROTECTION

Busbar protection must comply with the performance requirements of fast operating times (it is best to have sub-cycle operating times) for all busbar faults, security for external faults with heavy CT saturation, security during normal switching conditions, security with subsidence current present after clearing an external fault, and minimum delay for evolving faults. The busbar protection must also be dependable to detect high-resistance faults. All of these requirements must be achieved with minimum CT performance requirements. The logic shown in Figure 4, implemented in a numerical relay, meets the above performance requirements during all system operating conditions.

The logic includes numerous busbar protection elements. Each of the busbar protection elements consists of the following three elements [23] and [26]:

- Differential element using phasor values
- Directional element using phasor values
- Fault detection logic using instantaneous values

Figure 4 shows a block diagram of busbar protection logic that includes a differential element, a directional element, and fault detection logic. The figure shows only two of the current inputs (I01 and I02) connected. Because the relay accepts current inputs from CTs with ratio mismatch, the calculations for the differential elements are performed on per-unit values. The relay uses the highest CT ratio (CTR_{MAX}) of the installed CT ratios as a reference value in converting the input currents from ampere to per-unit values. Using Equation (1), the relay calculates a normalization factor value (K) for each terminal:

$$Knn = \left(\frac{CTR_{MAX} \bullet I_{NOM}}{CTRnn} \right) \tag{1}$$

Where:

Knn	=	K normalization factor for each terminal to convert current from ampere to per unit, nn = 01 through NN (NN denotes the maximum number of configured terminals)
CTR_{MAX}	=	Highest CT ratio of the terminals used in the terminal-to-bus-zone settings
I_{NOM}	=	Nominal CT secondary current (1 A or 5 A)
CTRnn	=	CT ratio of the specific terminal

Through use of the Knn factors, the relay calculates the current in per-unit values for each terminal as follows:

$$InnCR = \left(\frac{Inn}{Knn} \right) \tag{2}$$

Where:

InnCR	=	Per-unit current for Terminals 01 through NN in per unit
Inn	=	Current in amperes for Terminals 01 through NN

The following description corresponds to one of the protection zones of the scheme. The labels I01 and I02 refer to current inputs from Busbar Terminal I01 and Busbar Terminal I02.

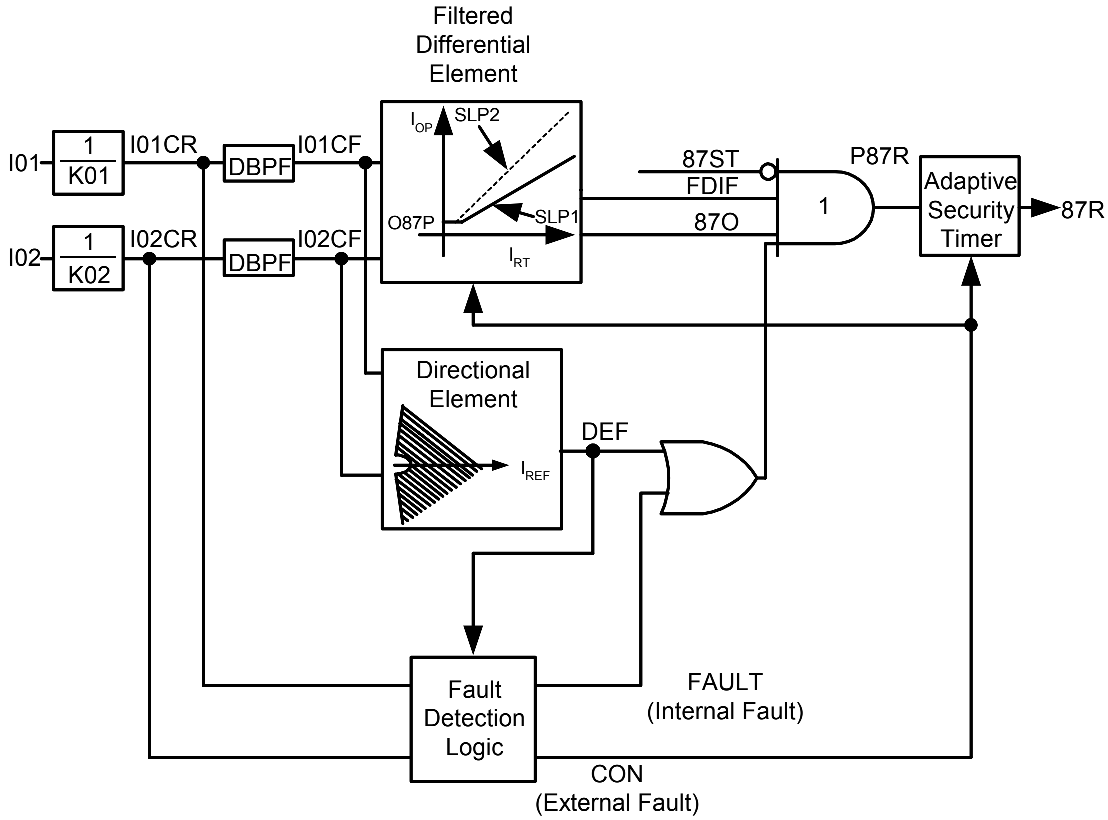


Figure 4 Block Diagram Showing the Logic for One of the Protection Zones

After the per-unit conversion, the normalized currents (I01CR and I02CR) follow two separate paths, as shown in Figure 4. One path is through a digital band-pass filter (DBPF) to the filtered differential element and the directional element; the other path brings the instantaneous values to the fault detection logic.

The digital band-pass filter (DBPF) is a one-cycle cosine filter. The cosine filter has its coefficients (CFC) evenly sampled from a cycle of a cosine waveform as follows:

$$CFC_k = \cos\left[\frac{2 \bullet \pi}{N} \bullet (k + 0.5)\right] \tag{3}$$

Where:

k	=	0, …, N–1
N	=	is the number of samples per cycle.

Filtered Differential Element

The filtered differential element uses the currents from each terminal in the protection zone to provide security in the presence of subsidence current that can result from the clearing of a heavy current fault. Using the output quantities from the digital band-pass filter, the element calculates the restraint quantity, I_{RT}, and the operating quantity, I_{OP}, according to Equation (4) and Equation (5). Figure 5 shows a block diagram of the elements necessary to obtain the differential characteristic used in the filtered differential elements. The differential element characteristic consists of two slopes: SLP1 and SLP2. SLP1 is effective for internal faults, and SLP2 is effective for external faults (when CON, external fault detection, is asserted). This slope adaptability adds security to the filtered differential element during external fault conditions. The filtered differential element has two outputs. Output FDIF indicates that I_{OP} is greater than I_{RT} • SLPn. The second output, 87O, indicates that I_{OP} is greater than the differential element threshold, O87P. Assertion of these two outputs indicates that the operating point is in the tripping region of the filtered differential element characteristic.

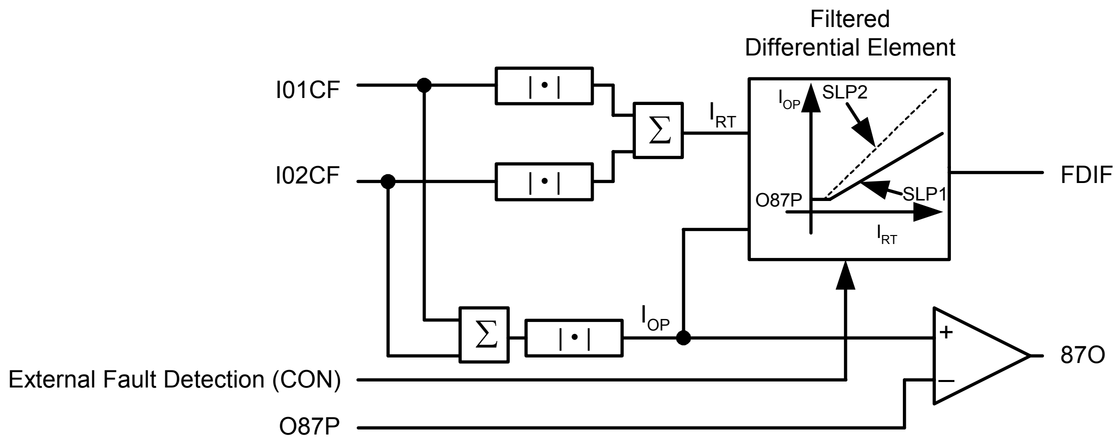


Figure 5 Filtered Differential Element

$$I_{RT} = |I01CF| + |I02CF| \tag{4}$$

$$I_{OP} = |I01CF + I02CF| \tag{5}$$

Where:

I01CF, I02CF = Filtered per-unit current values from Terminals I01 and I02

Directional Element

The directional element supervises the filtered differential element and provides additional security to the filtered differential element during external faults with heavy CT saturation [23]. Each protection zone has a directional element specific to that protection zone. The directional element uses the cosine-filtered currents from each terminal in a protection zone. The directional element selects one of the terminals in the protection zone as a reference and compares the direction of the current at this reference terminal with the direction of current at all other qualifying terminals in each protection zone. A qualifying terminal is a terminal with a current value greater than a pickup threshold, 50DSP; the directional element algorithm selects one of these currents as a reference. For each calculation, the relay uses the real part of the product of the terminal current and the conjugate of the current of the reference terminal [27]. When the angle between each of the selected terminals and the reference terminal is inside the directional element operating region (hatched area in Figure 4), the directional element asserts DEF to declare an internal fault.

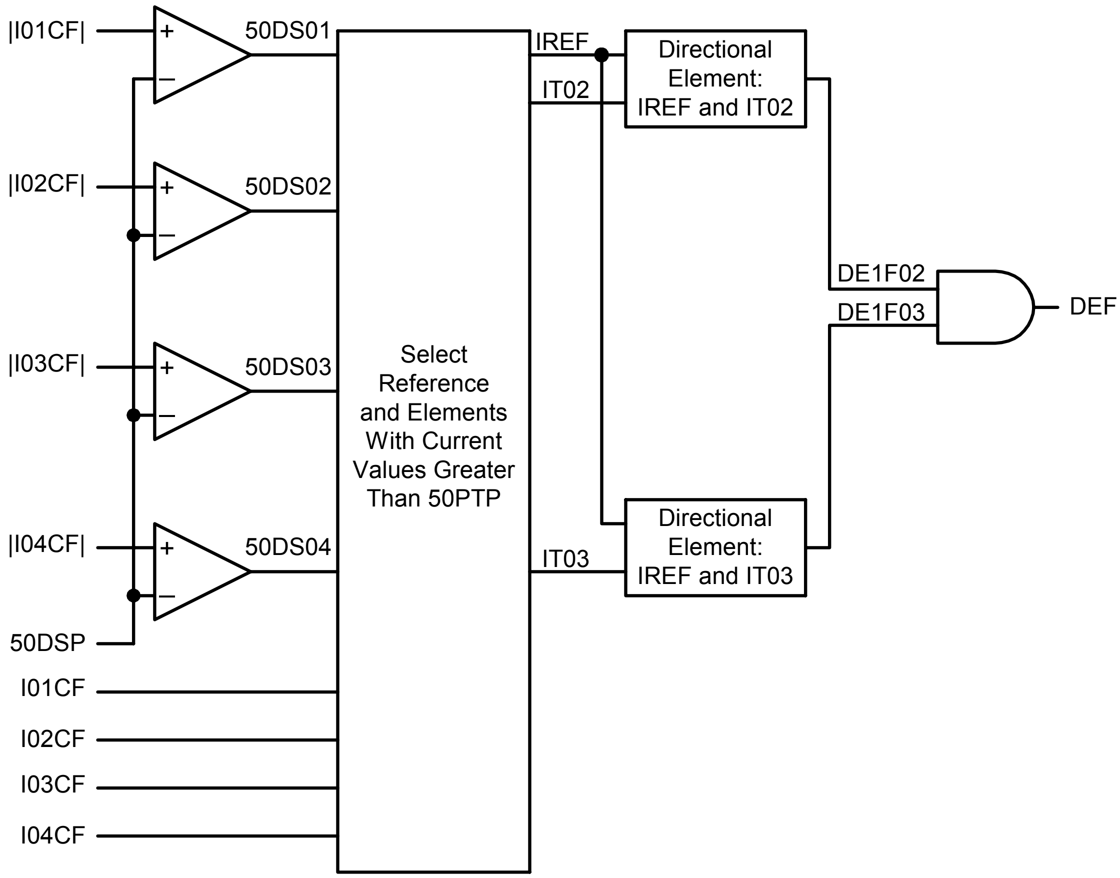


Figure 6 Adaptive Directional Element Logic

Refer to Figure 6 and consider the case of four terminals in the protection zone, with inputs labeled I01CF, I02CF, I03CF, and I04CF. Assume that the current magnitude at terminal I04CF is less than the 50DSP threshold. First, the directional element determines which terminals have phase current magnitude greater than the 50DSP threshold. Because the current magnitude of input I04CF is less than the 50DSP threshold, the relay selects only inputs I01CF, I02CF, and I03CF for further processing. The relay selects input I01CF as the reference (IREF) and compares the directions of current I02CF (IT02) and current I03CF (IT03) to this reference. The directional element output (DEF) asserts only if the direction of current at both IT02 and IT03 coincides with the direction of current at the reference terminal.

Fault Detection Logic

The fault detection logic, shown in Figure 7, distinguishes between external and internal faults. The external fault detection takes advantage of the fact that, for external faults, only the restraint current increases before CT saturation begins [28]. Figure 8 shows the I01CR and I02CR currents for an external fault condition where the CT in Terminal 02 exhibits saturation. The figure also shows the raw operating, I_{OPR}, and raw restraint, I_{RTR}, currents for the same external fault.

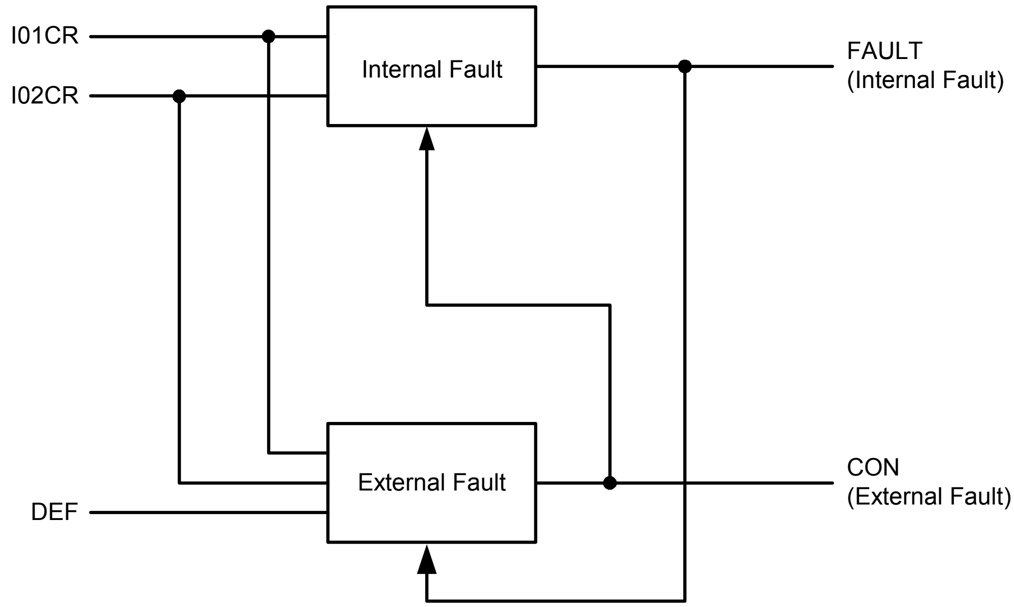


Figure 7 Fault Detection Logic for Distinguishing Between External and Internal Faults

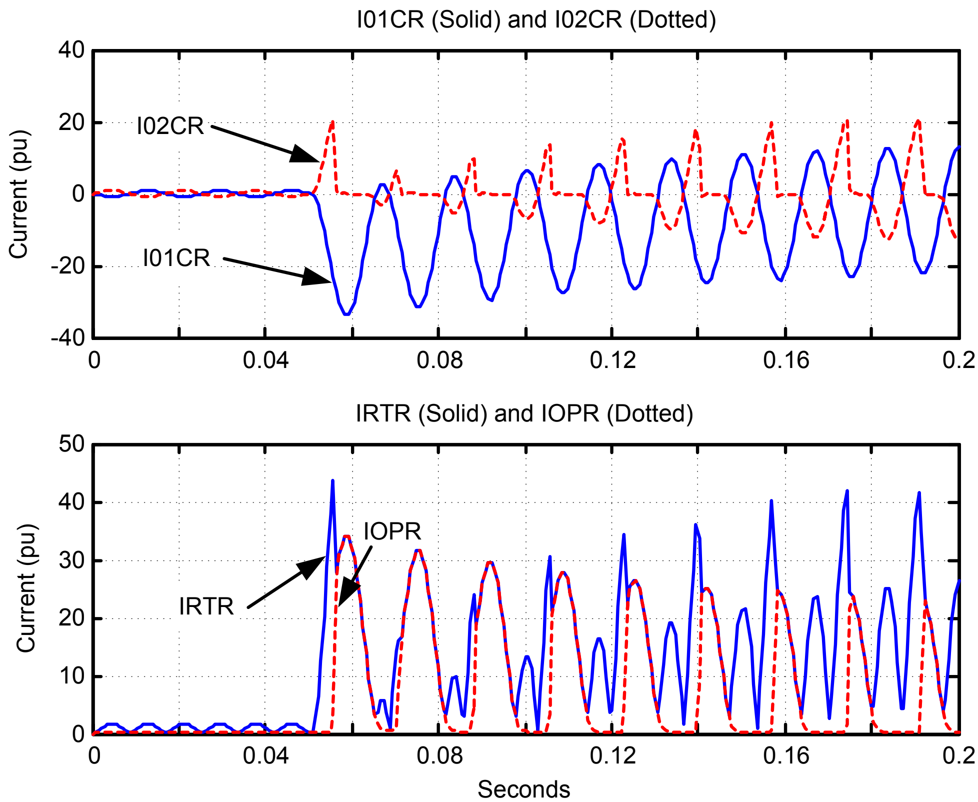


Figure 8 Raw Currents Provide Information to Detect External Faults

The external fault detection logic controls the relay operating mode and asserts indicator CON for external faults. During normal operating conditions, CON is deasserted. After an external fault, CON asserts and switches the relay to a high-security mode. During high-security mode, the following occurs:

- The slope of the differential characteristic changes from SLP1 to SLP2.
- The instantaneous differential element requires the operating point to be inside the differential element characteristic during two consecutive half cycles.
- The delay time of the adaptive security timer increases.

The logic in Figure 9 compares the change in the operating current, ΔI_{OPR}, to the change in the restraint current, ΔI_{RTR}, to detect external faults. If ΔI_{RTR} is present (ΔI_{RTR} greater than RTDI) without ΔI_{OPR} for a couple of milliseconds, the logic declares an external fault condition for 60 cycles (CON assertion). Asserting CON for 60 cycles can slow relay operation for evolving faults (where the fault begins as an external fault and then develops into an internal fault). To prevent delayed tripping, CON resets when either the directional element (DEF) detects an evolving fault or the internal fault detection logic (IFAULT) confirms an internal fault condition.

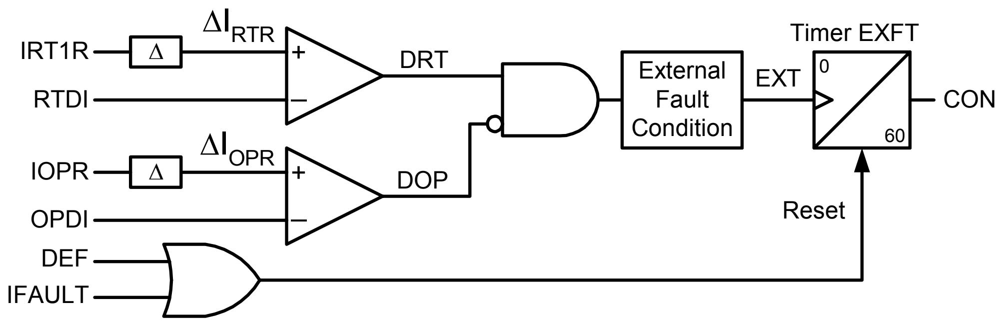


Figure 9 External Fault Detection Logic Compares Changes in the Restraint Current, ΔI_{RTR}, to Changes in the Operating Current, ΔI_{OPR}, to Detect External Fault Conditions

Figure 10 shows the internal fault detection logic consisting of the instantaneous differential element, the consecutive measurement fault detection logic, and the fast fault detection logic. RDIF, the output from the instantaneous differential element, forms the input into the consecutive measurement fault detection logic and the fast fault detection logic. The consecutive measurement fault detection logic declares an internal fault when differential current still exists (RDIF asserted) on a consecutive measurement a half cycle after assertion of the instantaneous differential element (RDIF) [17]. When this logic detects an internal fault, IFAULT asserts.

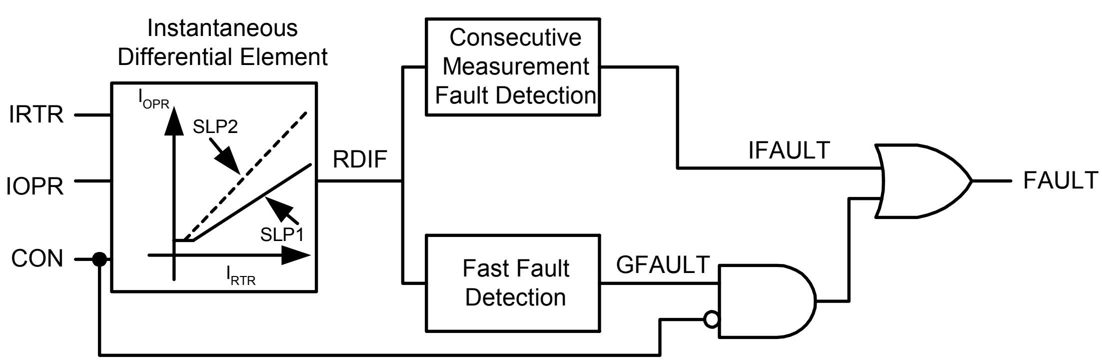


Figure 10 Internal Fault Detection Logic Provides Fast and Dependable Protection

If surge (lightning) arrestors are installed on busbars, a path to ground exists when these devices conduct, resulting in operating current in the differential elements. The fast fault detection logic qualifies the operating current with a time delay (typically 0.167–0.25 cycle) to differentiate between operating current resulting from surge arrestor conduction and operating current because of internal faults. If the fast fault detection logic detects an internal fault, GFAULT asserts. Internal fault indication, FAULT, asserts upon assertion of IFAULT or GFAULT.

Differential Element Output Logic

In addition to requiring that the operating point be inside the tripping region of the filtered differential element characteristic, the differential element output logic requires assertion either of the directional element (DEF) or the internal fault detection (FAULT) to declare an internal fault (P87R assertion). Assuming that there is no CT trouble (87ST deasserted), the P87R bit drives a security timer that controls the final output (87R) of the differential element. Figure 11 shows the four conditions from the relay measuring and control logic that must be fulfilled to start the security timer:

- An output from the filtered differential element, FDIF.
- An output from the filtered differential element threshold, 87O.
- An output from either the directional element (DEF) or the internal fault detection logic (FAULT).
- No output from the sensitive differential element (87ST). That is, there is no CT trouble.

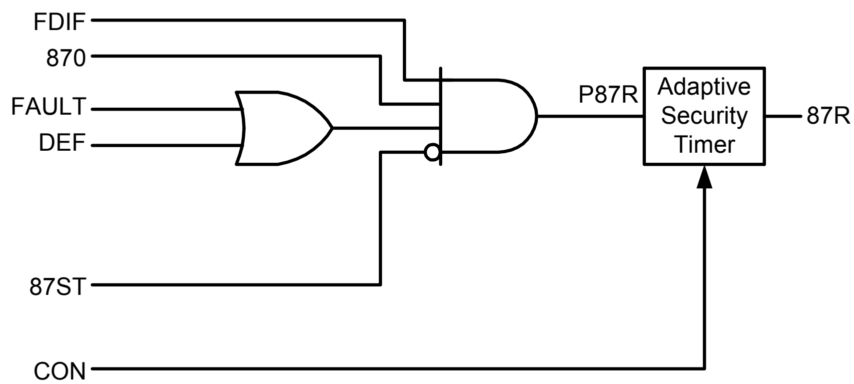


Figure 11 Differential Element Output: Final Conditions and Adaptive Security Timer

With satisfaction of the four differential element output logic conditions, the output P87R starts the adaptive security timer. CON also controls the security timer time setting: when CON asserts, the relay increases the time delay to increase security for the protection element. If P87R asserts for longer than the pickup time of the security timer, 87R asserts to indicate a fault in the differential zone.

BREAKER FAILURE PROTECTION

Busbar protection was the first station-wide protection. Breaker failure protection became the second station-wide protection function when it replaced the use of remote Zone 2 distance relay elements for local back-up protection. While one relay provided system-wide busbar protection, implementation of breaker failure protection was traditionally through the use of separate relays, one breaker failure relay for each station breaker.

Low-impedance busbar protection incorporates the current input from each terminal and a trip signal to the circuit breaker on each terminal. If we now include the breaker failure initiation signal, we have all the components necessary for breaker failure protection in one location. Breaker failure protection, therefore, is an integral part of low-impedance busbar protection, making the protection scheme more economical.

Breaker failure protection offers perhaps the best example of a protection function with a variety of applications. Not only do different busbar configurations require different breaker failure circuitry, but application practices also differ noticeably for any given busbar configuration. For example, a breaker-and-a-half busbar configuration may affect breaker failure protection because of the fault current distribution. For such busbar configurations, two circuit breakers at one line end must operate to clear a line fault. Figure 12 shows Fault F1, for which both Circuit Breaker TD and Circuit Breaker TG must operate to clear the fault on the line. For certain faults, the current distribution may be such that Circuit Breaker TD carries the bulk of the fault current, as shown in Figure 12.

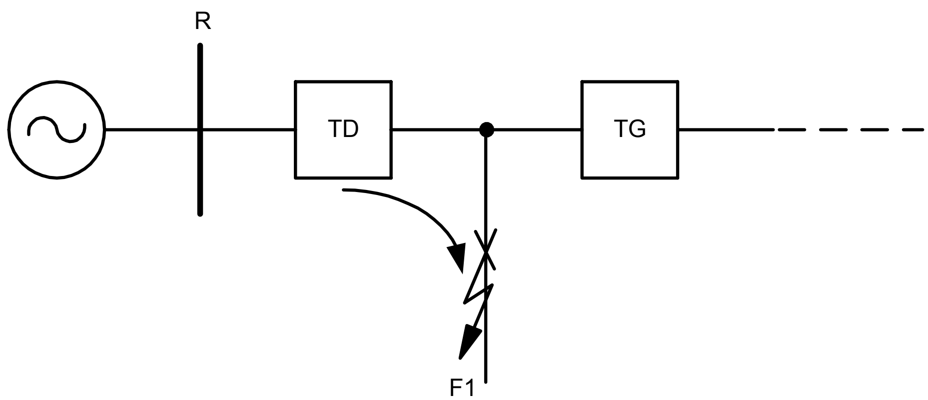


Figure 12 Current Distribution for Fault F1 With Circuit Breaker TD and Circuit Breaker TG Closed

Because of the current distribution, Terminal TG may have only enough current to assert the breaker failure current element threshold when Circuit Breaker TD opens, as shown in Figure 13.

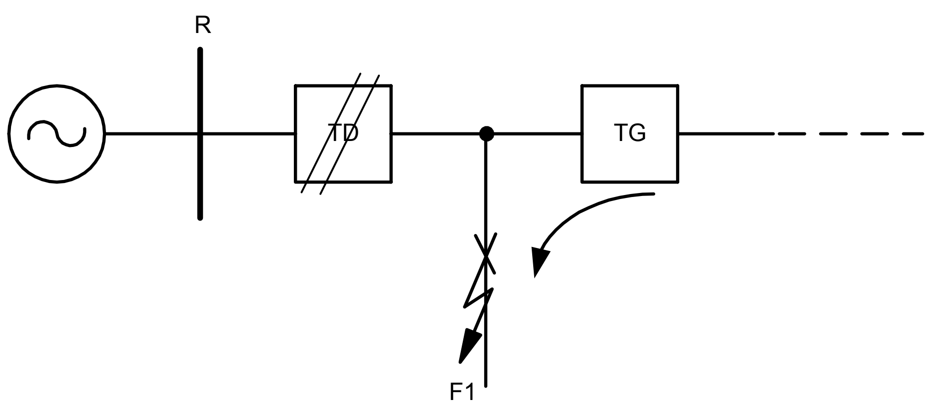


Figure 13 Current Flow for Fault F1 After Circuit Breaker TD Opened

For protection philosophies requiring both current and breaker failure initiate signals, uneven current distribution delays initiation of breaker failure protection for Terminal TG until Circuit Breaker TD interrupts the current. However, both circuit breakers receive the trip signal at the same time and should operate simultaneously. To obtain this simultaneous operation, we initiate breaker failure protection on receipt of the breaker failure initiation signal only (current below relay pickup threshold).

Some application philosophies call for the use of independent breaker failure relays, where the relays are sometimes installed in a separate panel dedicated to breaker failure protection only. In this case, the output from the breaker failure relays (or lockout relay) is connected to the low-impedance busbar protection to take advantage of the zone-selection function in the busbar protection relay. Through use of the zone-selection function, it is possible to selectively trip a minimum of circuit breakers, instead of indiscriminately tripping all circuit breakers to clear the fault. Other application philosophies call for a retrip function, in which the logic initiates an additional attempt to trip the failed circuit breaker before stripping the busbar.

Another factor influencing breaker failure protection is the presence of subsidence current. Figure 14 shows decaying current following interruption of an offset current signal. The subsidence current resulting from energy trapped in a CT magnetizing branch after fault clearance can delay the resetting of overcurrent elements.

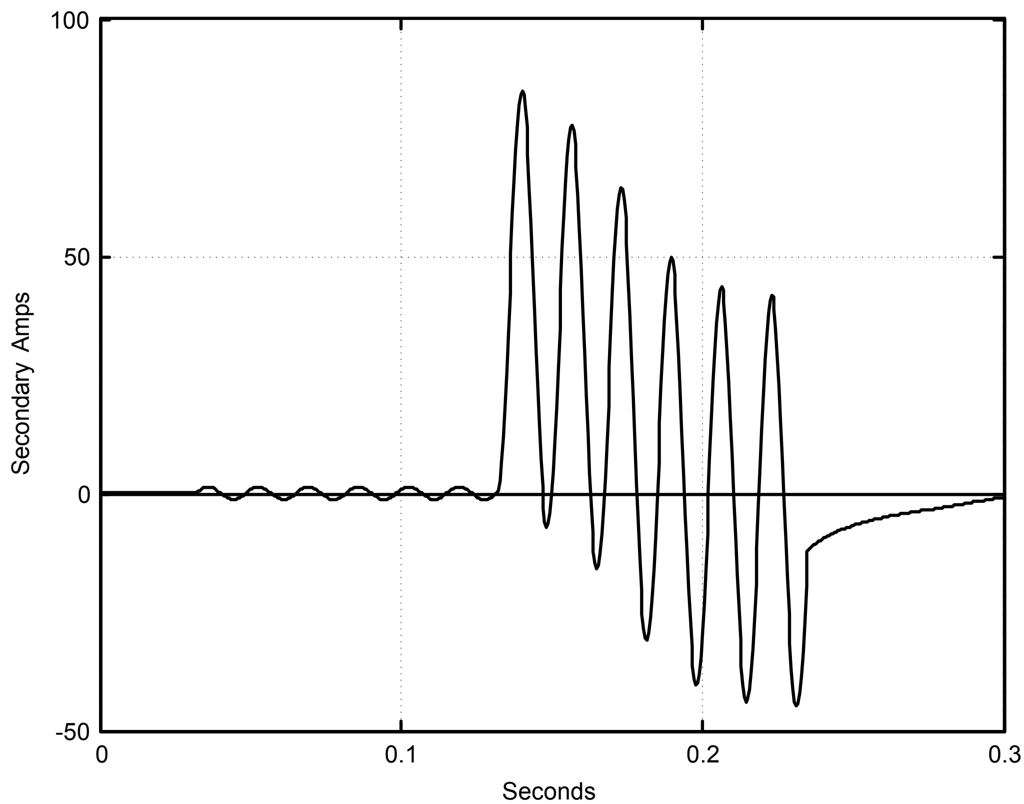


Figure 14 Decaying Current Still Flowing in the CT After Primary Fault Interruption

This delay can result in breaker failure relay overcurrent elements still being picked up although primary current has stopped flowing. Figure 15 shows a method whereby the relay declares an open-phase condition in less than one cycle. Because the open-phase output supervises the relay breaker failure logic (Figure 21), the breaker failure overcurrent elements reset in less than one cycle.

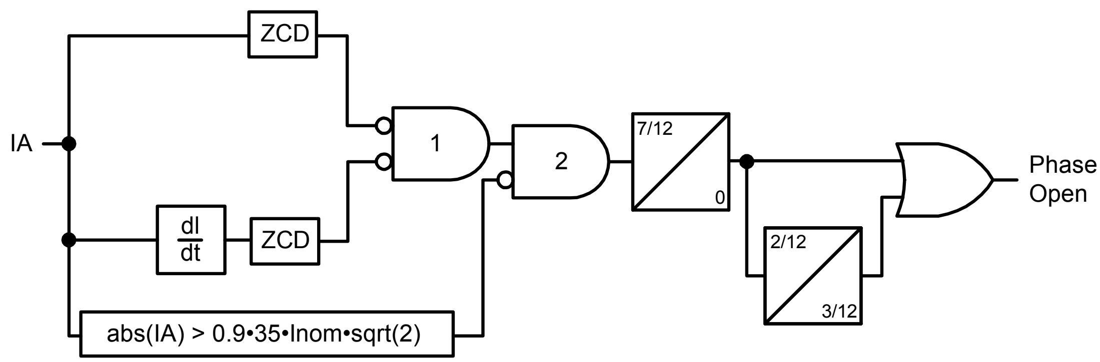


Figure 15 Algorithm for Resetting the Overcurrent Elements in Less Than One Cycle

To detect an open-phase condition, the relay uses the principle that ac current changes direction and crosses the zero line within a specified interval, while a decaying dc current does not cross the zero line. The ac signal (without dc offset) crosses the zero line every half cycle. However, testing the signal every half cycle is not often enough to detect an open-phase condition in less than one cycle. To the zero crossing detection (ZCD), we add evaluation of the signal slope to detect the minimum and maximum values of the current signal. This evaluation adds an additional measurement between two zero crossings and provides the relay with the ability to detect an open-phase condition in less than one cycle. Figure 16 shows the two points of measurement on a signal without dc offset current.

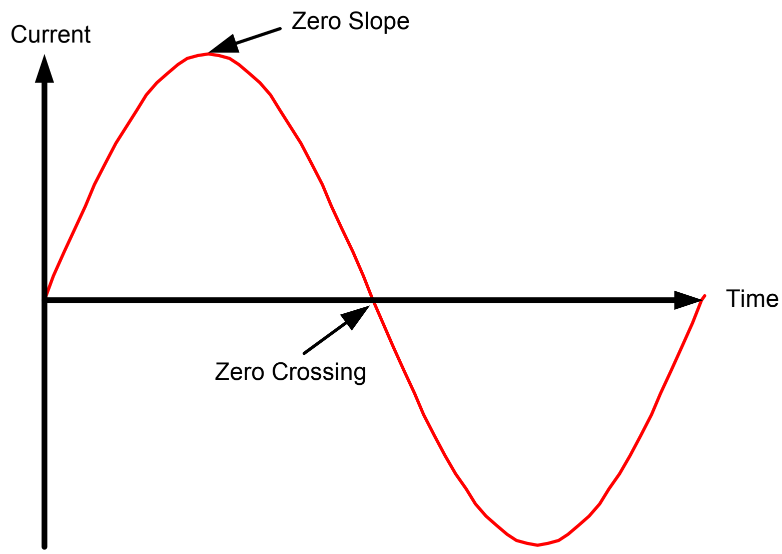


Figure 16 Current Signal Without DC Offset

Figure 17 shows the measurement on a signal with dc offset current. Notice the zero-crossing time difference of nearly a quarter cycle between the signal without dc offset (t1) and the signal with dc offset (t2). Evaluating the zero slope of the signal provides an additional measurement, making possible the detection of an open-phase condition in less than one cycle.

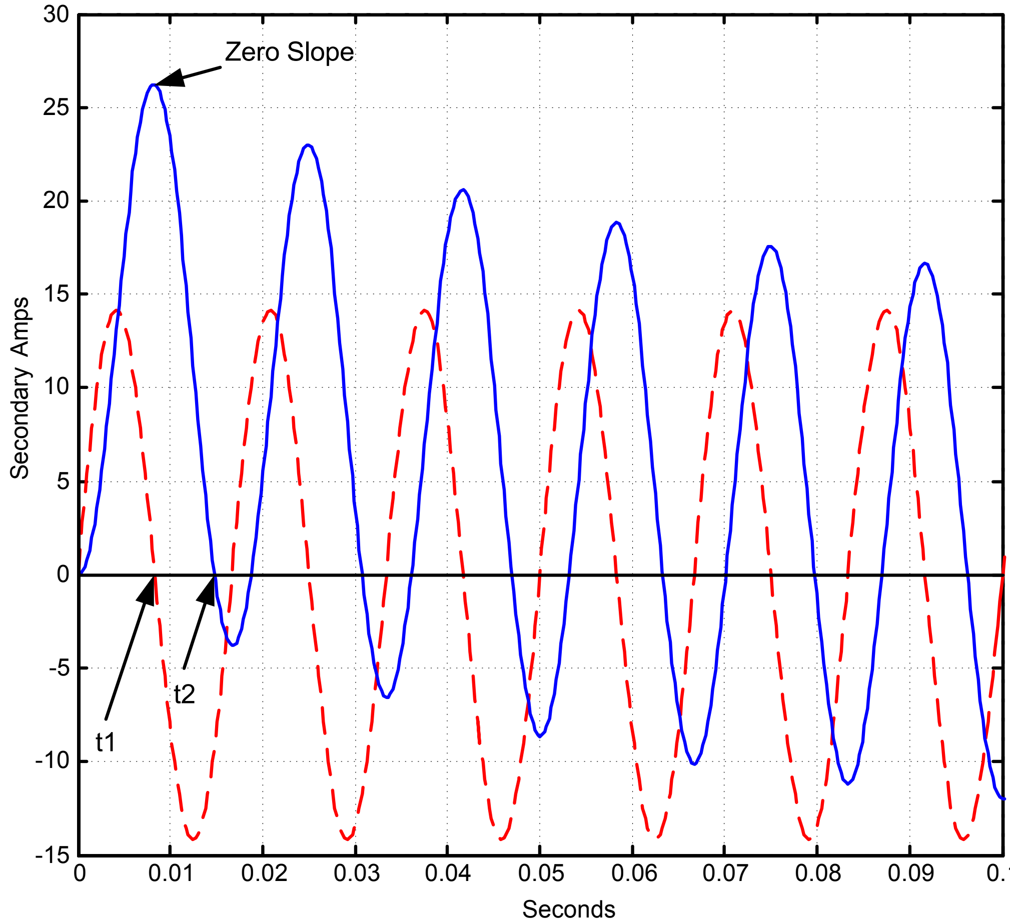


Figure 17 Current Signal With DC Offset

The final element in Figure 15 (abs(IA) > 0.9•35•Inom•sqrt(2)) guards against fictitious zero-slope conditions resulting from A/D saturation, as shown in Figure 18.

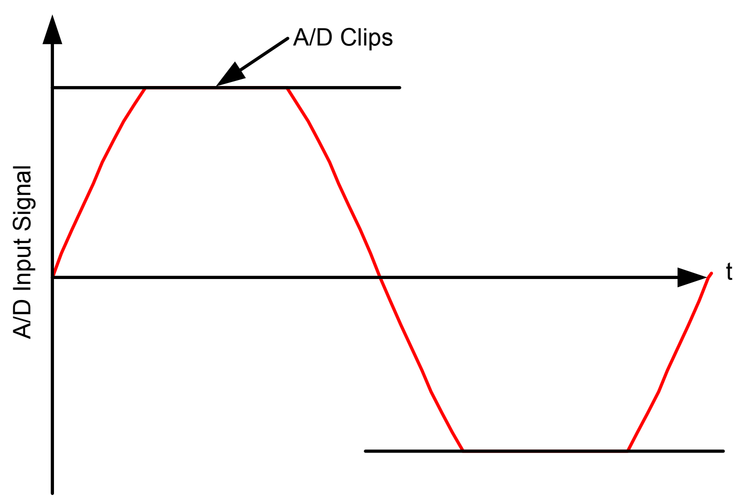


Figure 18 Fictitious Zero-Slope Conditions From A/D Saturation

Clearly, breaker failure protection must be flexible enough to accommodate all of the different applications and protection philosophies, while providing secure and reliable operation for all system conditions. At a minimum, the following two options should be available for breaker failure protection:

- Schemes using the internal breaker failure protection of the busbar protection (Figure 19). These schemes send a breaker failure initiation (normally a trip output from a protective relay) signal to the bus protection relay. This application requires that the busbar protection include the breaker failure protection, zone selection, trip logic, and output contacts to operate the appropriate breakers. This option includes two variations: schemes that seal in the breaker failure initiation signal, and schemes that do not seal in the breaker failure initiation signal. We discuss the two variations in more detail later in the paper.

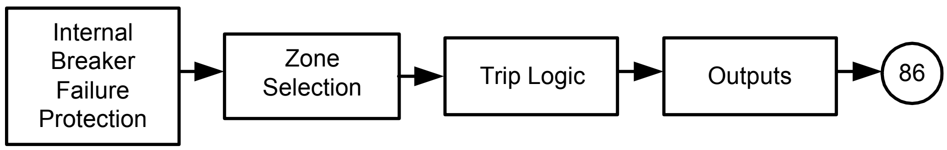


Figure 19 Schemes Using the Internal Breaker Failure Protection of the Busbar Protection

- Schemes equipped with external breaker failure relays (BFR). These schemes (such as in Figure 20) send a bus trip (output from the breaker failure relay on the terminal panel) command to the bus protection relay that requires zone selection, trip logic, and output contacts to operate the appropriate breakers or the lockout relay.

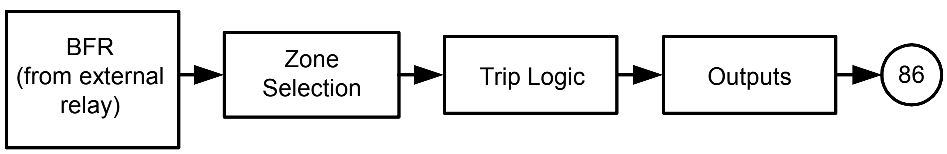


Figure 20 Schemes Equipped With External Breaker Failure Relays

Using Internal BFR: Initiating Signal Not Sealed In

Because the busbar protection does not seal in the breaker failure initiation signal, use this option when the breaker failure initiation signal is present continuously for the duration of the breaker failure period. If the trip signal falls away for one processing interval longer than the debounce dropout time setting, the breaker failure timers reset. Figure 21 shows the breaker failure logic for this application. Wire the breaker failure initiation signal, typically a trip output contact from a protection relay, to the Breaker Failure Initiation input.

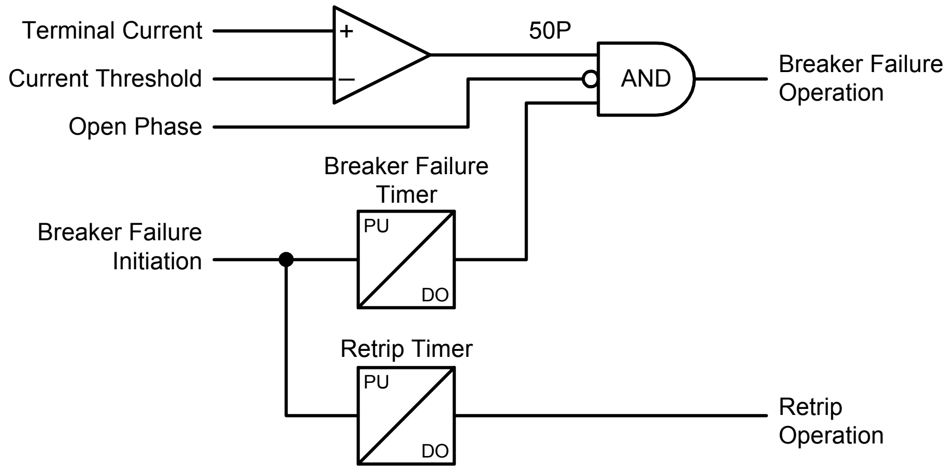


Figure 21 Breaker Failure Logic

If the fault current exceeds the Current Threshold input, 50P asserts immediately following fault inception. When the Breaker Failure Initiation input asserts, the Breaker Failure Timer and the Retrip Timer start timing. If 50P remains asserted when the Retrip Timer expires, the relay issues a retrip signal. When the Breaker Failure Timer expires, the relay issues a breaker failure trip output that causes tripping of all circuit breakers identified by the zone selection algorithm. If the circuit breaker opens successfully, neither the Breaker Failure Timer nor the Retrip Timer assert. Likewise, if the breaker failure initiation signal deasserts before either timer expires, the timers drop out regardless of the 50P value. The Open Phase input turns the AND gate off in less than one cycle after primary fault current interruption, even during subsidence current conditions.

Using Internal BFR: Initiating Signal Extension/Seal–In

This logic adds an input stage to the Breaker Failure Logic (Figure 21) to provide the choice of either extending the breaker failure initiation signal or sealing in the breaker failure initiation signal. Figure 22 shows the input stage logic for both breaker failure initiating input extension (AND Gate 1) and seal-in (AND Gates 1 and 2) functions.

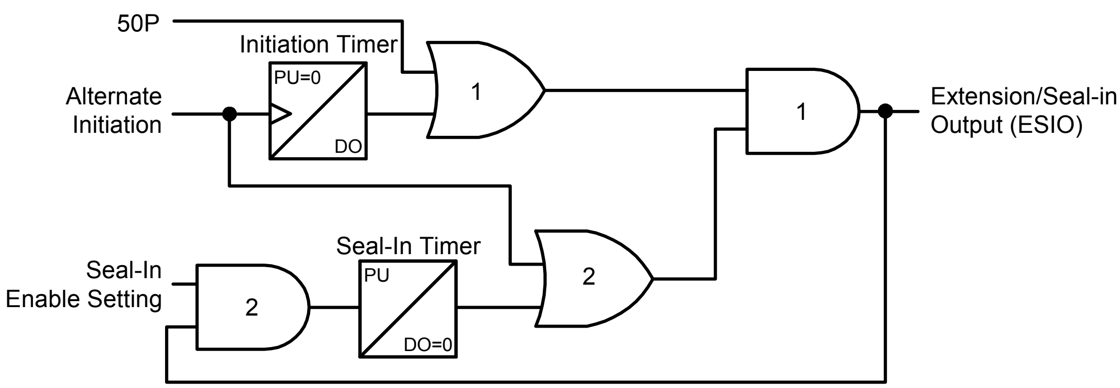


Figure 22 Circuit Breaker Failure Initiation Extension and Seal-In

Use the extension option when the protection philosophy requires both current and breaker failure initiate signals applied simultaneously to the breaker failure relay, but current is not immediately available. This is the case in applications where two breakers (Breaker 1 and Breaker 2) must open to interrupt fault current, such as in breaker-and-a-half and ring bus configurations. Using a combination of the Breaker Failure Logic and the Breaker Failure Seal-In and Extended Breaker Failure Initiation logic, we create a good compromise for this protection philosophy. Wire the breaker failure initiation signal from the protection relay to the Alternate Initiation input instead of the Breaker Failure Initiation input (Figure 21), and assign the Output ESIO to the Breaker Failure Initiation input. Figure 23 shows the combined logic.

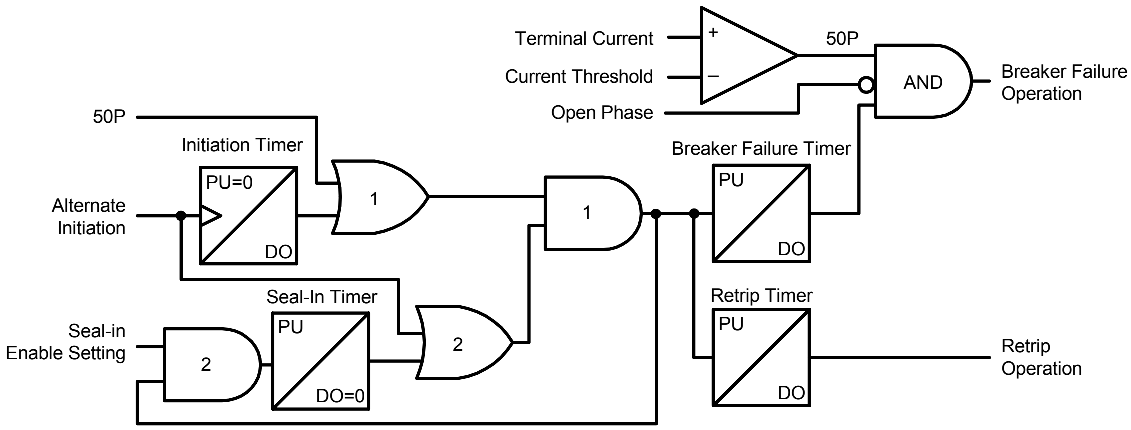


Figure 23 Breaker Failure Protection Logic With Alternate Initiation

When the Alternate Initiation input asserts, AND Gate 1 turns on, asserting Output ESIO in Figure 22. Because Output ESIO is now assigned to the Breaker Failure Initiation input, the Breaker Failure Timer begins timing.

Assume that Breaker 1 opens first in a breaker-and-a-half configuration. When Breaker 1 opens, enough current flows through Breaker 2 to assert 50P. Note that 50P replaces the output from the Initiation Timer and keeps AND Gate 1 turned on, sustaining the input to the breaker failure timers. Although we initiate the breaker failure protection without current present, we do so only for the operating time of Breaker 1. The Initiation Timer drop-off time should be longer than the time Breaker 1 takes to interrupt the current. This delay ensures that, after Breaker 1 opens, the breaker failure timers run only when both the breaker failure initiation signal and 50P are present.

Breaker failure initiating input seal-in uses the seal-in option if the breaker failure initiation signal is not continuous and fault current is available. On receipt of the breaker failure initiation signal, AND Gate 1 turns on. The output from AND Gate 1 starts the breaker failure timers and turns on AND Gate 2. If the initiation signal is present for longer than the Seal-In Timer pickup setting, the output from AND Gate 1 seals in for as long as 50P is present.

Using External BFR

Schemes equipped with external breaker failure relays require only zone-selection logic and trip output contacts in the busbar protection relay. When the output from the breaker failure relay asserts the External Breaker Failure input on the busbar relay, the busbar relay uses the zone-selection logic to select the appropriate terminals that are in the same zone as the failed circuit breaker and issues a trip signal to corresponding circuit breakers or lock out relays, depending on the protection design (Figure 24).

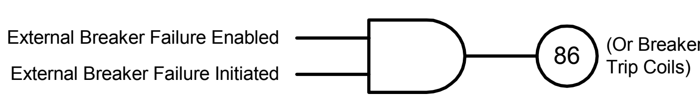


Figure 24 Logic for External Breaker Failure

BUSBAR DIFFERENTIAL AND BREAKER FAILURE PROTECTION TRIP

In general, busbar protection philosophy calls for the operation of a minimum of circuit breakers to clear a fault. Zone selection uses disconnect auxiliary inputs to assign current inputs to the appropriate differential elements to calculate the operating and restraint currents necessary for busbar protection. We use the same disconnect auxiliary input information to assign trip signals to the appropriate circuit breakers following either differential operation or breaker failure operation. Although both differential protection and breaker failure protection use the zone selection algorithm to determine the terminals in the affected bus-zone, the breaker failure trip algorithm differs from the differential trip algorithm in one important aspect. Before issuing trip signals to affected terminals, the breaker failure algorithm must first determine the specific zone to which the failed breaker is connected. Thereafter, the breaker failure trip algorithm and differential trip algorithm are the same. Figure 25 shows the differential trip algorithm, and Figure 26 shows the breaker failure trip algorithm.

The purpose of the bus differential trip algorithm is to send trip signals to the circuit breakers according to the differential element operation. To send the correct trip signals, the differential trip algorithm uses differential element information and zone selection information to determine which breakers to trip. Following a differential operation, the differential trip algorithm identifies all terminals in the faulted bus-zone and then sends trip signals to all circuit breakers in the faulted bus-zone.

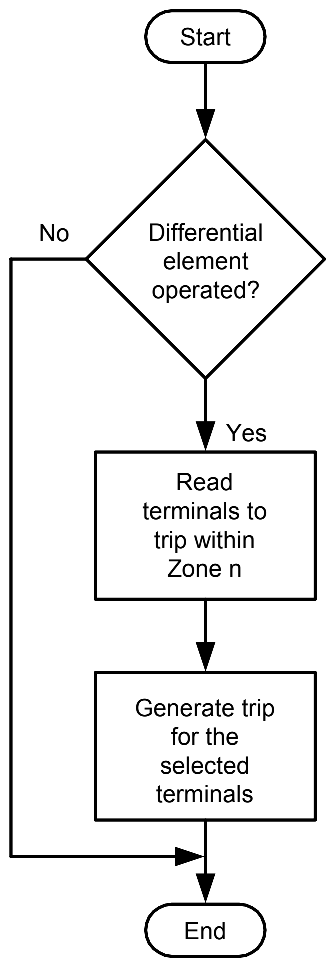


Figure 25 Bus Differential Trip Algorithm

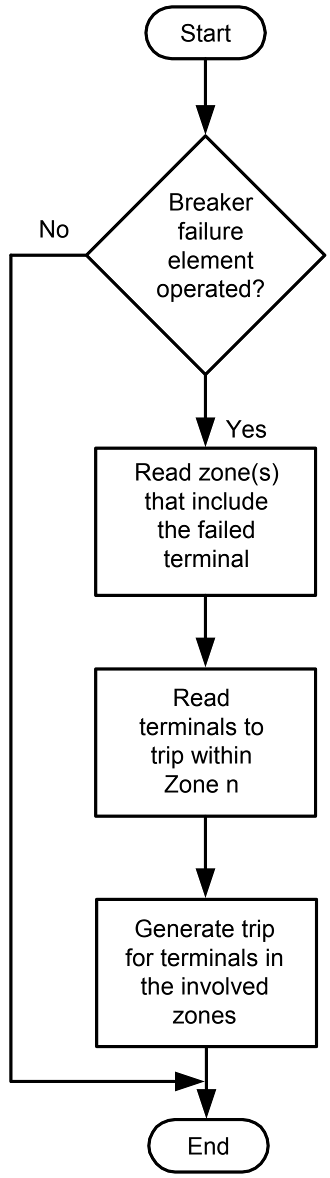


Figure 26 Breaker Failure Trip Algorithm

The purpose of the breaker failure trip algorithm is to send trip signals to circuit breakers according to a particular breaker failure operation. The breaker failure trip algorithm uses breaker failure trip information from each terminal and zone selection information to determine which breakers to trip. Following a breaker failure relay operation, the breaker failure trip algorithm identifies the bus-zone(s) to which the failed terminal is connected, as well as all other terminals in the same bus-zone(s) as the faulted breaker. The breaker failure trip algorithm then sends trip signals to all of these circuit breakers.

APPLYING THE BUSBAR PROTECTION RELAY

Because busbar layouts vary from station to station, and busbar philosophies vary from utility to utility, the protection system this paper describes provides discrete, configurable functions instead of fixed logic that could be unsuitable for a particular application. Combine these discrete functions both to tailor the relay configuration to the substation layout and primary plant and to comply with specific protection philosophies. For example, the protection system provides check-zone protection for those protection philosophies that require check-zone protection. Because check-zone protection is not required for all configurations, the user can configure check-zone protection when it is required. Figure 27 shows a block diagram of these discrete functions.

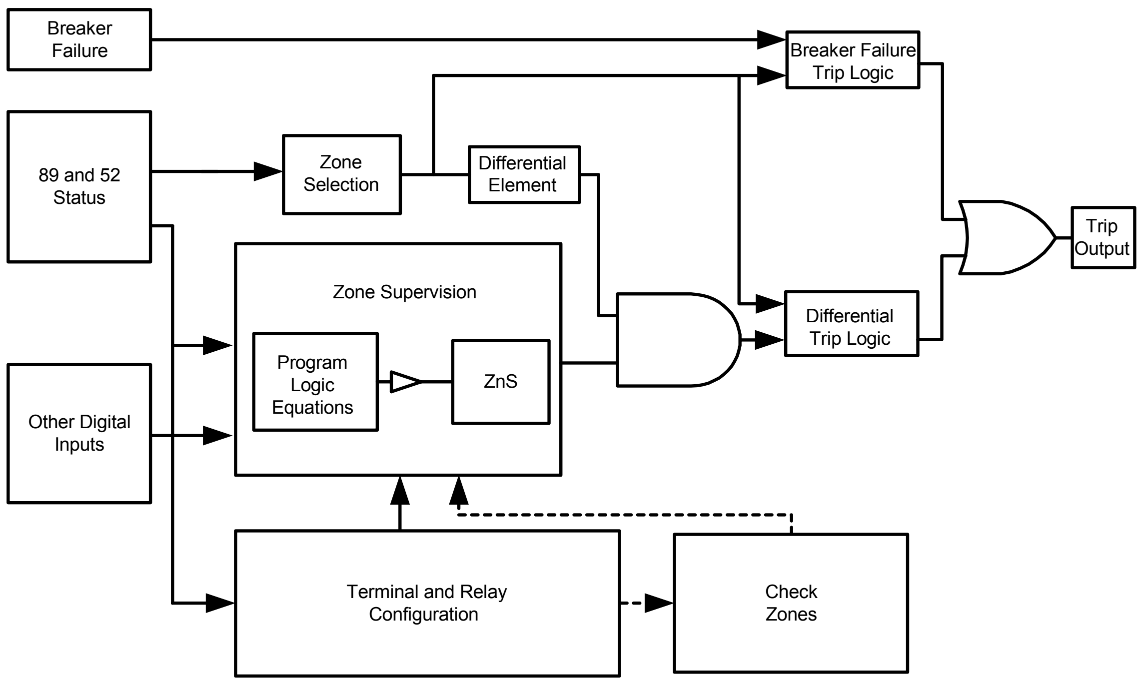


Figure 27 Block Diagram of Discrete Functions

Disconnect (89) and Circuit Breaker (52) Status

Generally, disconnect auxiliary contacts provide station status information in the form of digital inputs. Zone selection logic uses the disconnect auxiliary contacts to dynamically assign the appropriate current inputs (from the current transformers) to the correct differential elements. Therefore, dynamic zone selection, and ultimately differential element performance, depend on correct selection, operation, and relay interpretation of the disconnect auxiliary contacts.

In Figure 28, closing Disconnect 891 connects the terminal to Bus-Zone 1. A normally open auxiliary contact (89A) from Disconnect 891 connects to Digital Input 1 of the relay, and a normally closed auxiliary contact (89B) from Disconnect 891 connects to Digital Input 2 of the relay. Current from the terminal CT connects to Analog Input 1 of the relay. The relay uses the status of disconnect auxiliary contact 89B to assign CTs to and remove CTs from differential element calculations. When Disconnect 891 closes, auxiliary contact 89B opens, and the relay assigns the terminal current to the differential element of the appropriate bus-zone. Conversely, when Disconnect 891 opens, auxiliary contact 89B closes, and the relay does not consider the terminal current in the differential calculations of any bus-zone differential element.

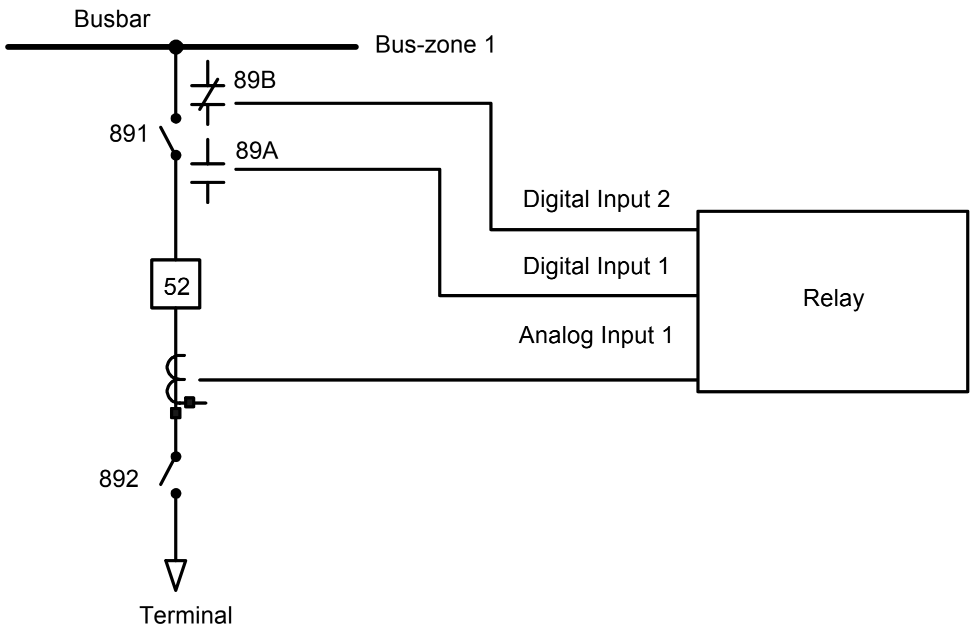


Figure 28 Typical Terminal CT and Disconnect Inputs

Disconnect auxiliary contact status by itself does not ensure relay security during all auxiliary contact combinations; the relay must receive the disconnect status information with reference to specific positions of the main contact. We reference these specific positions to the so-called arcing point. In an open-to-close disconnect operation, we identify the arcing point as the position on the disconnect travel path where primary current starts to flow. In a close-to-open operation, we identify the arcing point as the position on the disconnect travel path where primary current ceases to flow. Table 5 shows the correct disconnect auxiliary selection relative to the arcing point.

Table 5 Disconnect Auxiliary Contact Requirements to Ensure Correct Differential Operation

Operation	Requirement
From disconnect open-to-disconnect close operation	Assign the currents to the applicable differential element before the disconnect reaches the arcing point, i.e., before primary current flows.
From disconnect close-to-disconnect open operation	Remove the current from the applicable differential element only once the disconnect has passed the arcing point, i.e., after primary current stops flowing.

In a disconnect main contact open-to-close operation, disconnect auxiliary contact 89B must open before the disconnect main contacts reach the arcing point. When disconnect auxiliary contact 89B opens, the relay assigns the terminal current to the differential elements. Assigning the current from the terminals to the differential elements before primary current flows ensures correct differential element operation.

In a disconnect main contact close-to-open operation, disconnect auxiliary contact 89B must remain open until the disconnect main contacts have passed the arcing point. When disconnect auxiliary contact 89B closes, the relay removes the terminal current from the differential element, and the relay no longer considers the current in the differential calculations.

Figure 29 shows the disconnect auxiliary contact requirements with respect to the arcing point. The position of 0 percent travel in Figure 29 indicates the position at which the main contacts are fully open, and the 100 percent position indicates the position at which the main contacts are fully closed.

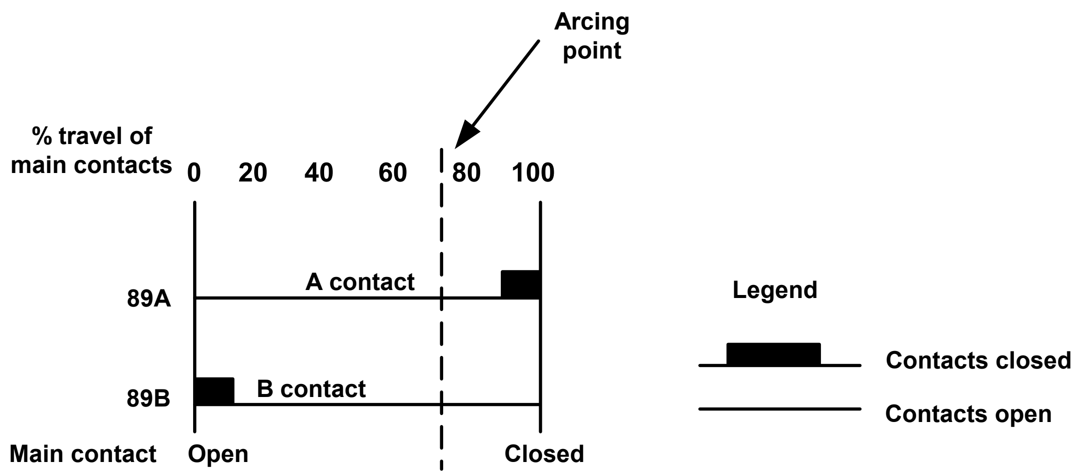


Figure 29 Disconnect Auxiliary Contact Requirements With Respect to the Arcing Point

Although the disconnect auxiliary contacts convey disconnect status when the disconnect is either fully open (89B closed) or fully closed (89A closed), the intermediate position, when both 89A and 89B contacts are open, is a period of uncertainty. Applying the principle of (disconnect) NOT OPEN = (disconnect) CLOSED prevents relay misoperation during the intermediate position, or when an open circuit exists on the disconnect auxiliary contact cable. With this principle, the relay considers the disconnect OPEN only when auxiliary contact 89B is closed. Table 6 shows the four possible disconnect auxiliary contact combinations and the way the relay interprets these combinations.

Table 6 Disconnect A and B Auxiliary Contact Status Interpretation

Case	89A	89B	Interpretation of Disconnect Status
1	Open	Open	Disconnect considered CLOSED
2	Open	Closed	Disconnect considered OPEN
3	Closed	Open	Disconnect considered CLOSED
4	Closed	Closed	Disconnect considered CLOSED

Clearly, successful operation of zone selection depends on the performance of the 89B disconnect auxiliary contact; the 89A auxiliary contact provides only indication of the completion of the disconnect travel. Table 6 (Interpretation of Disconnect Status column) shows that the relay interprets the disconnect as always closed, except for Case 2, when auxiliary contact 89B is closed. Therefore, the relay assigns the input currents to the applicable differential elements for Case 1, Case 3, and Case 4. The following discussion considers the four cases in more detail.

Disconnect Open-to-Close Operation

Figure 30 shows the disconnect main contacts starting to travel in an open-to-close operation (Case 2 in Table 6). Auxiliary contact B is still closed, and auxiliary contact A is open. With the B contact closed, the relay considers the disconnect to be open and removes the terminal current from all differential elements. Case 2 is the only combination of auxiliary contacts for which the relay considers the disconnect main contacts to be open.

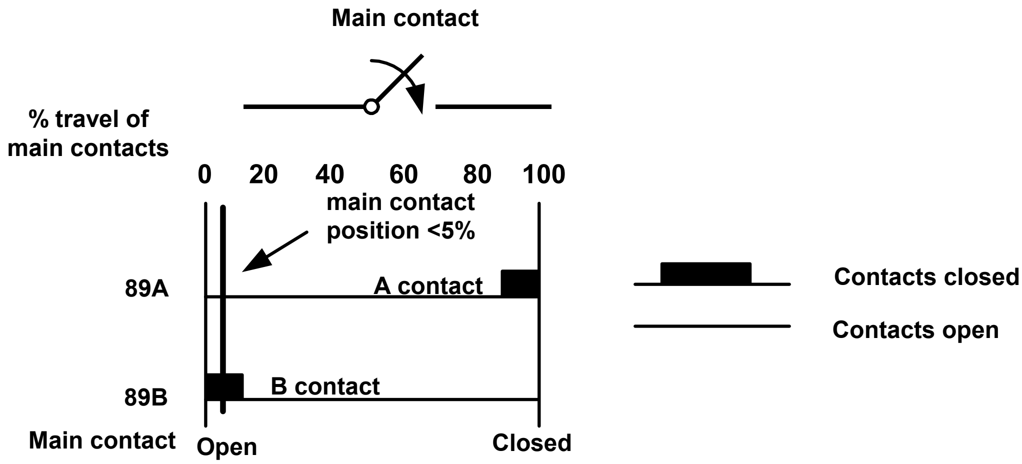


Figure 30 Disconnect Auxiliary Contact B Closed: the Relay Considers the Disconnect Open

<u>Intermediate Position</u>

Figure 31 shows the intermediate position (Case 1 in Table 6) in a disconnect open-to-close operation, with both A and B contacts open for a period of time. When the relay considers the disconnect closed, it assigns CT currents to the applicable differential elements. Because auxiliary contact B opens well in advance of the arcing point, the relay assigns CT currents to applicable differential elements before primary current flows. If primary current flows before the relay assigns CT currents to applicable differential elements, the relay may misoperate.

Because the relay cannot distinguish between the intermediate position and a permanent disconnect wiring open-circuit condition, we must monitor the duration of the intermediate position. Thus, when both A and B contacts are open, a timer (disconnect alarm timer) starts to time. The disconnect alarm timer stops timing when the A contact closes at the end of the disconnect travel.

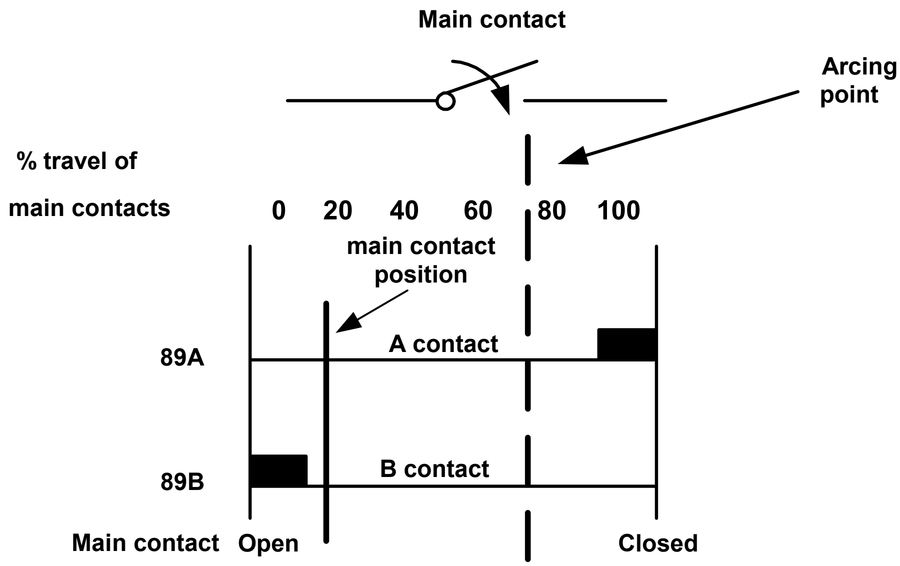


Figure 31 Both Auxiliary Contacts are Open: the Relay Considers the Disconnect Closed

By choosing auxiliary contacts that will change status as soon as disconnect travel starts and close only near the end of travel, we can measure the intermediate position duration accurately. Should the disconnect fail to complete the open-to-close operation and stop in the intermediate position, the CT currents remain assigned to the applicable differential elements. In this case, the relay issues an alarm to indicate disconnect failure.

Auxiliary Contact A Closes

Figure 32 shows contact status after auxiliary contact A closes, with the main contact past the arcing point and approaching the end of the close operation (Case 3 in Table 6). When auxiliary contact A closes, the disconnect switch alarm timer stops timing.

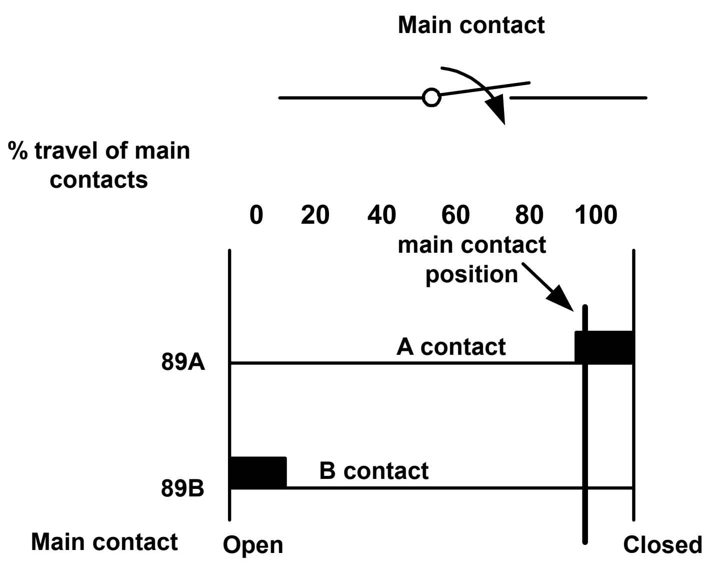


Figure 32 Disconnect Auxiliary Contact A Closed: the Relay Considers the Disconnect Closed

Disconnect Open and Closed Simultaneously

Case 4 is an abnormal condition, with the disconnect auxiliary contacts showing the disconnect main contact to be open and closed simultaneously. This condition can arise when one auxiliary contact mechanically jams in one position, or when one auxiliary contact is short-circuited. The differential element is secure for this condition, because the relay considers the disconnect closed during this abnormal condition. The disconnect alarm asserts after the alarm timer expires, indicating a contact discrepancy.

Close-to-Open Operation

For the close-to-open operation, CT currents must remain assigned to the differential elements for as long as primary current flows. When auxiliary contact A opens, (Case 1 in Table 6), we again enter the intermediate position, as depicted in Figure 31. In the intermediate position, the CT currents remain assigned to the differential elements, and the relay is secure. Only when auxiliary contact B closes (Figure 30) does the relay remove CT currents from the differential elements.

Disconnect Monitor Logic

Figure 33 shows logic to realize the (disconnect) NOT OPEN = (disconnect) CLOSED principle. Disconnect auxiliary contact 89A01 (normally open) and disconnect auxiliary contact 89B01 (normally closed) represent the two disconnect auxiliary contacts from Terminal 1. Use the top output (Disconnect Status) in the terminal-to-bus-zone equations. This output ensures that the relay considers the disconnect OPEN only when auxiliary contact 89B is closed and auxiliary contact 89A is open.

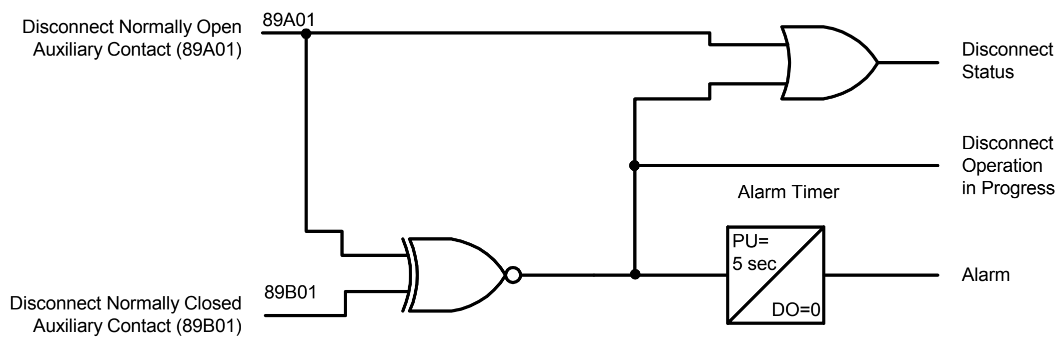


Figure 33 Disconnect Auxiliary Contact A Closed

The alarm output asserts when the disconnect auxiliary contacts remain in the intermediate position longer than the Alarm Timer setting. Generally, the alarm output asserts when the disconnect cable is either open circuited or short circuited. In addition, the logic provides a Disconnect Operation In Progress output that indicates when the disconnect is in the intermediate position.

Tie Breaker Considerations

Zone selection provides a method for dynamically reassigning CT currents to appropriate differential elements in complex busbar arrangements. This reassignment is necessary when disconnects change status to connect terminals from one zone to another. Tie breakers (also called buscouplers and bus sectionalizing breakers) form the demarcation between zones, i.e., there is either a buscoupler or a bus sectionalizing breaker between two zones.

Installing buscoupler and bus sectionalizing breakers (tie breakers) creates additional bus-zones at substations to limit the impact of busbar faults on customers. Faults on busbars with multiple zones usually result in the loss of only one of the zones, rather than the complete substation. (A fault between the circuit breaker and CT with tie breakers configured in overlap is the exception; a fault here causes loss of both zones.) Tie breakers can be operational tools for controlling load flow, or they can serve as "spare" breakers at substations with transfer facilities. The status of the tie breaker is, therefore, a function of operational requirements; it is possible for a tie breaker to be either open or closed during normal conditions.

Tie Breaker Closing Onto a Fault

The tie-breaker operational flexibility could result in network operating conditions leading to busbar protection misoperation. For example, consider the substation shown in Figure 34. The tie-breaker circuit breaker auxiliary contact 52A forms part of the conditions for CT consideration in the differential calculations (see *Protection Zone Selection* on page 4), i.e., the 52A and both disconnects must be closed before the differential element considers the tie-breaker CTs in the differential calculations. Although the disconnects are closed, the tie-breaker circuit breaker is open and the differential calculations do not consider the tie-breaker CT inputs in the differential calculation. Fault F1 represents grounding straps inadvertently left on the busbars in Protection Zone 1.

When energizing the busbar in Zone 1, the Feeder 1 circuit breaker is open, and the tie-breaker circuit breaker is about to close. If primary current flows before the tie-breaker circuit breaker auxiliary contacts change state to assign the tie-breaker CTs to the appropriate differential elements, the grounding straps at F1 appear as an internal fault for Zone 2, causing the Protection Zone 2 differential elements to misoperate.

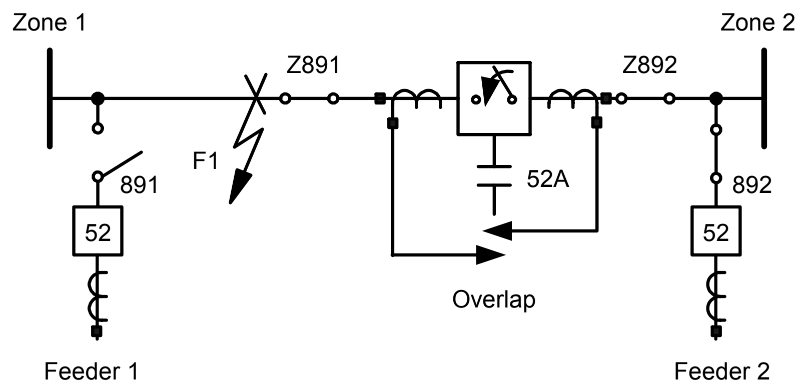


Figure 34 Closing the Bus Sectionalizing Circuit Breaker Onto a Faulted Busbar

To prevent relay misoperation for Fault F1, we need to insert the tie-breaker CTs into the differential calculations before primary current flows. Figure 35 shows logic that inserts the tie-breaker CTs into the differential calculations, thereby preventing misoperation for Fault F1.

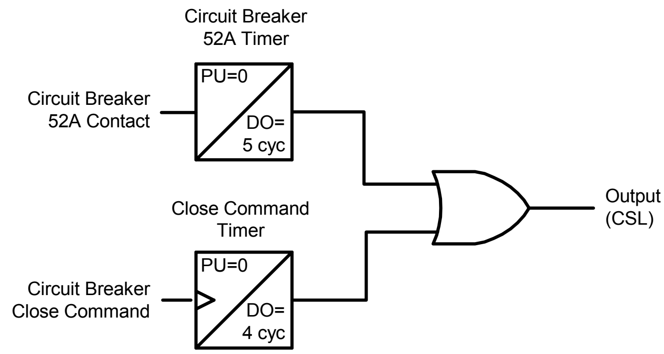


Figure 35 Logic for Preventing Differential Element Misoperation From Tie-Breaker Contact Timing

To use the logic in Figure 35, wire a tie-breaker circuit breaker status contact (52A) and a close command from the tie-breaker control switch to the relay. Assign the tie-breaker contact (52A) to the Circuit Breaker 52A Contact input of the logic, and assign the tie-breaker close command to the Circuit Breaker Close Command input of the logic. Use the output of the logic (CSL) in the tie-breaker terminal-to-bus-zone settings to assign the terminal currents to the appropriate differential elements. The Circuit Breaker 52A input and Circuit Breaker Close Command input are in parallel and complement each other, providing accurate circuit breaker status during open-to-close and close-to-open circuit breaker operations.

For an open-to-close operation, the Circuit Breaker Close Command input and the logic Output (CSL) assert simultaneously (on the rising edge of a circuit breaker close command). When the logic Output (CSL) asserts, the tie-breaker terminal-to-bus-zone programmable control equation asserts, and the relay considers the tie-breaker CTs in the differential calculations. Inserting the CTs into the differential equations before primary current flows prevents misoperation for Fault F1. Because the Close Command Timer pickup considers the rising edge of the close command, the Close Command Timer drop-out time delay seals in output CSL to allow the circuit breaker auxiliary contact to close. A drop-out time delay setting of 4 cycles provides ample time for the circuit breaker auxiliary contact to close. Once the circuit breaker auxiliary contact closes, the Circuit Breaker 52A input (Figure 35) asserts and keeps the logic output (CSL) asserted.

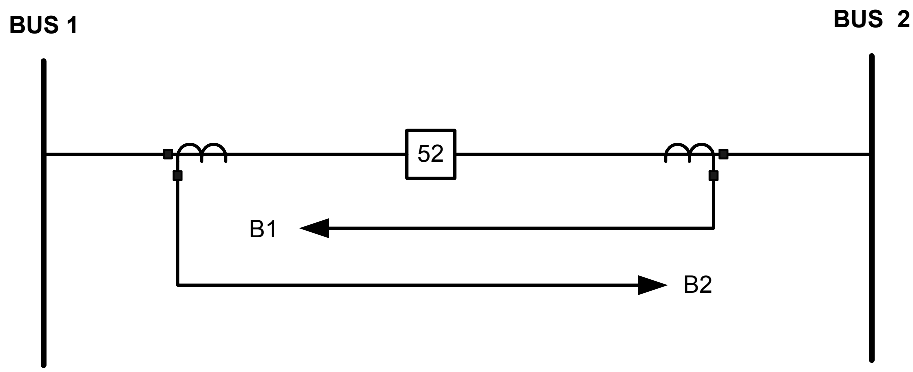
For a close-to-open operation, the opposite applies. For this operation, we must prevent premature CT removal from the differential equations. Circuit Breaker 52A input follows the breaker status: the input is deasserted when the circuit breaker is open and asserted when the circuit breaker is closed. The Circuit Breaker 52A Timer (DO) maintains the breaker close status for the drop-out time delay setting. During this delay, CSL is still asserted, allowing the circuit breaker time to interrupt the primary current before the relay removes the CTs from the differential equations.

Tie-Breaker Configurations

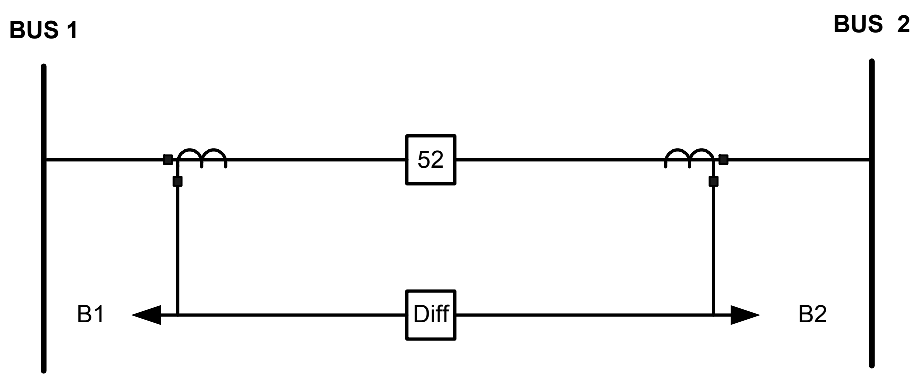
Tie breakers are generally configured according to one of three options shown in Figure 36. Cost, fault clearance time, and the impact of busbar faults on customers determine final selection. The three options are as follows:

- CT either side of the breaker with overlap
- CT either side of the breaker with breaker differential
- CT on one side of the breaker, single or two cores (two cores shown) with overlap[1]

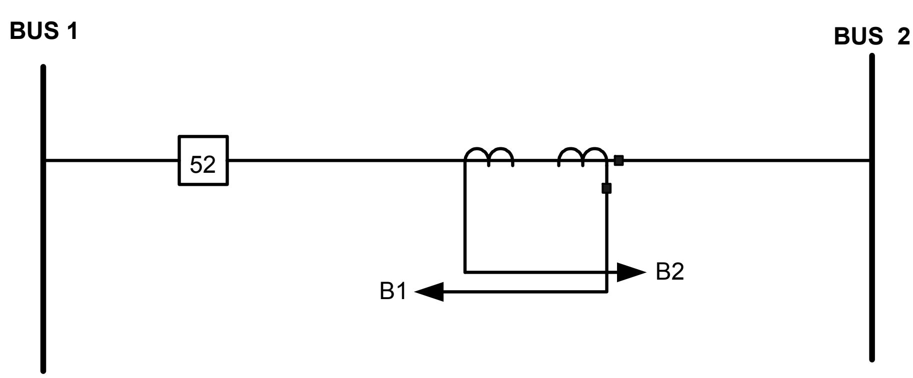
[1] The substation protection system this paper describes provides, with input from a single CT core, busbar protection for both zones of which the tie breaker is a part. Because only one current input is necessary to protect both zones for a single CT tie-breaker application, the analog inputs normally used for the second tie-breaker zone become available for an additional terminal.



(A) Two CTs, overlap



(B) Two CTs, breaker differential



(C) Single CT, overlap

Figure 36 Tie-Breaker Configurations

For Figure 36 (A) and (B) above, there must be three CTs on either side of the tie breaker (a total of six CTs). At higher voltages (particularly at transmission-level voltage), free-standing CTs (as opposed to bushing CTs) are very expensive, and Figure 36 (C) presents real cost savings. However, for higher voltage levels, better system performance is necessary, and CT availability for transfer purposes may dictate free-standing CT requirements.

For this discussion, clearing time is the complete interruption of fault current, not the opening of a specific circuit breaker. The distinction is important because, in Figure 36 (B) and (C), fault current still flows when the tie-breaker circuit breaker opens for a fault between the tie breaker and the CT.

“Zones lost” is, as the name implies, the number of tripped zones. Zones lost is an indication of the station-wide effect of a busbar fault on customers. The number of tripped zones influences both busbar layout and tie-breaker configuration decisions. For example, consider Fault F1 between the CT and the bus sectionalizer in Figure 37.

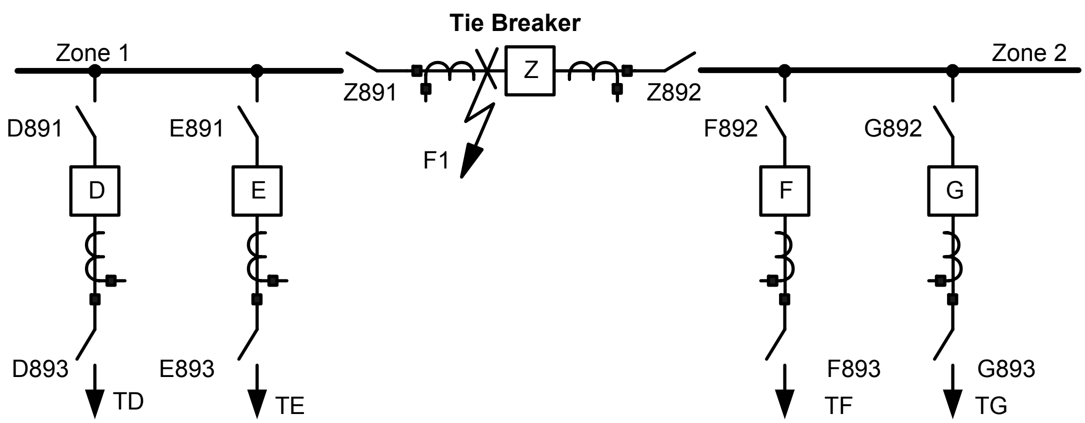


Figure 37 Fault F1 Between CT and Breaker

For an overlap application (Figure 36 (A)), busbar protection trips the tie breaker and all terminals in both Zone 1 and Zone 2. In this case, two zones are lost. For a breaker differential application (Figure 36 (B)), only one zone is lost, but at the expense of delayed tripping for faults between the tie breaker and CT (see Figure 39). Let us consider the impact on the power system of a fault between the tie breaker and CT for each of the three tie-breaker configurations.

Case A: CT at Both Sides of the Breaker With Overlap

Consider Fault F1 in Figure 38. Because the area between the CTs on either side of the tie breaker is common to both zones, Fault F1 results in both zones tripping instantaneously.

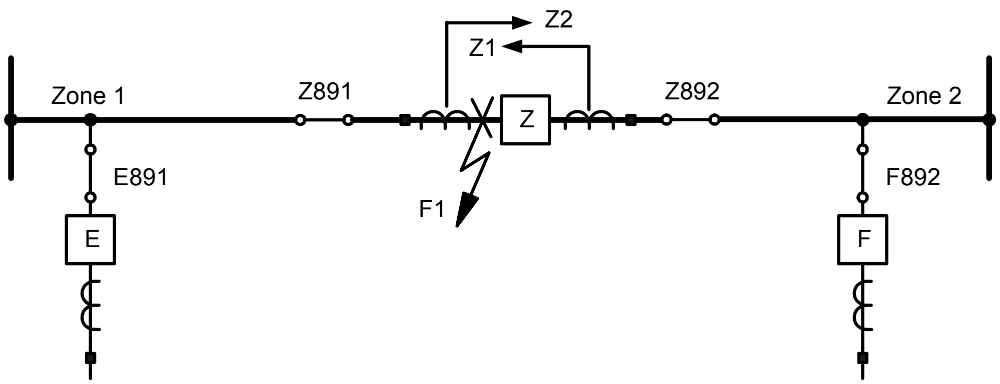


Figure 38 Two CTs, Overlap

The engineering tradeoff for instantaneous clearance of faults between the circuit breaker and CT is the loss of both zones.

Case B: CT Either Side of the Breaker With Breaker Differential

Figure 39 shows breaker differential protection across the tie breaker.

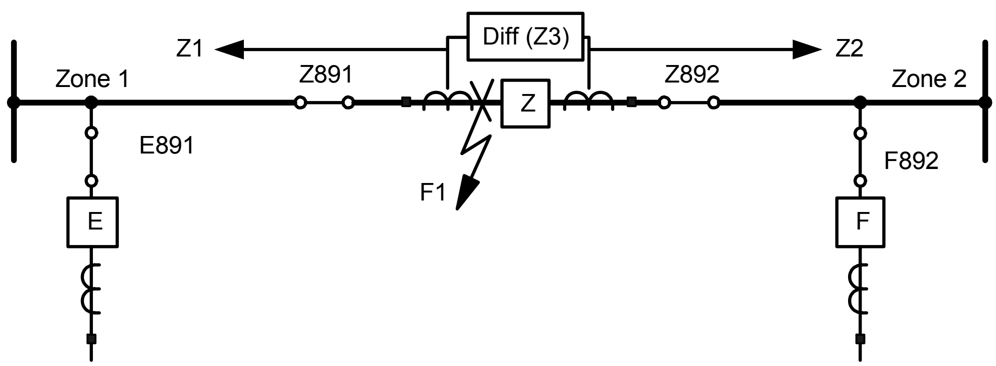


Figure 39 Two CTs, Breaker Differential

Fault F1 is now external to both Protection Zone 1 and Protection Zone 2, but the fault is internal to the breaker differential (Z3). The breaker differential protection trips the tie breaker and removes the tie-breaker CTs from Zone 1 and Zone 2 after the circuit breaker time delay of 5 cycles. With the tie-breaker circuit breaker open, only those terminals connected to Protection Zone 1 (Circuit Breaker E in Figure 39) contribute to the fault.[1] Only the tie breaker and Breaker E trip for this fault.

Here, the tradeoff is delayed busbar fault clearance to trip the minimum of zones, i.e., terminals in Zone 1 (Breaker E) have to wait for the tie breaker to trip before tripping terminals in Zone 1. Figure 40 shows an addition to the logic in Figure 35 to include an accelerated trip input. This feature provides an input for removing the tie-breaker CTs sooner than the dropout delay of 5 cycles.

[1] Because the relay removed the tie-breaker CTs when the tie breaker tripped, Zone 1 is now unbalanced and trips.

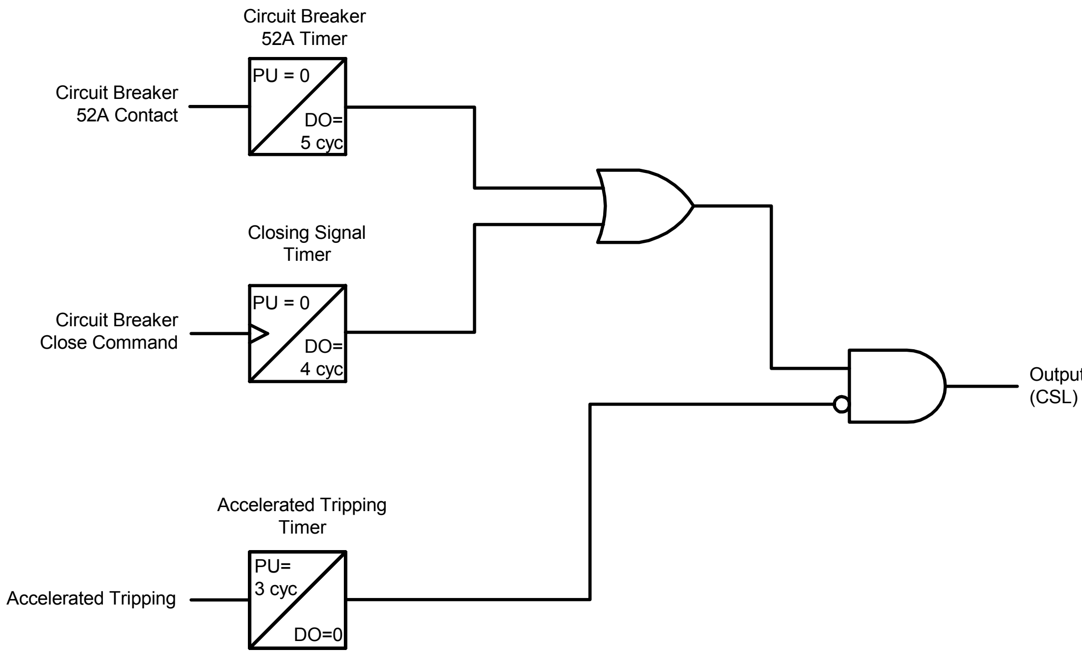


Figure 40 Logic With Accelerated Tripping to Prevent Differential Element Misoperation Because of Tie-Breaker Contact Timing

Select the accelerated trip input with care; this input defeats the coupler security logic. One solution is to use an output from the breaker differential element (Z3 in Figure 39) as the Accelerated Tripping input. With Accelerated Tripping Timer set to 3 cycles, CSL deasserts within 4 cycles to remove the tie-breaker CTs from the Zone 1 and Zone 2 differential elements (allowing one cycle for differential element operation) after fault inception.

Case C: Single CT, Overlap

Although only three CTs are necessary for a three-phase system, technical performance is the worst for the single CT application as shown in Figure 41.

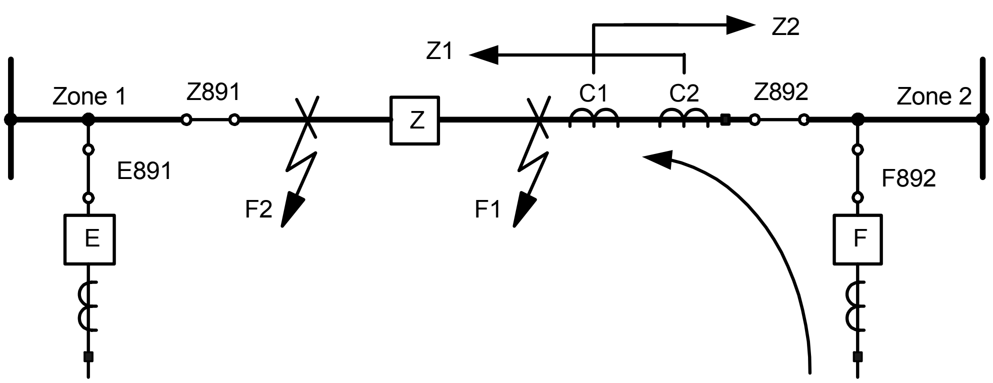


Figure 41 Single CT, Overlap

When Fault F1 occurs, Protection Zone 2 is stable. However, the Protection Zone 1 busbar protection immediately trips all terminals connected to Protection Zone 1 and the tie-breaker circuit breaker. Tripping Circuit Breaker E and the tie-breaker circuit breaker, however, does not clear Fault F1, and fault current from Circuit Breaker F still flows through the tie-breaker CT. At the same time, protection also initiates breaker failure protection on Breaker F and the tie breaker. The fault current causes the breaker failure protection of the tie breaker to continue timing, although the tie-breaker circuit breaker tripped. After the tie-breaker circuit breaker failure timer expires, all circuit breakers in Protection Zone 2 trip. Both Protection Zone 1 and Protection Zone 2 trip to clear this fault.

If delayed tripping for all Zone 1 busbar faults is acceptable, use a combination of zone supervision and coupler security logic to prevent tripping Zone 1 for faults between the tie-breaker circuit breaker and the CT. Figure 42 shows the combination of coupler security logic and zone supervision.

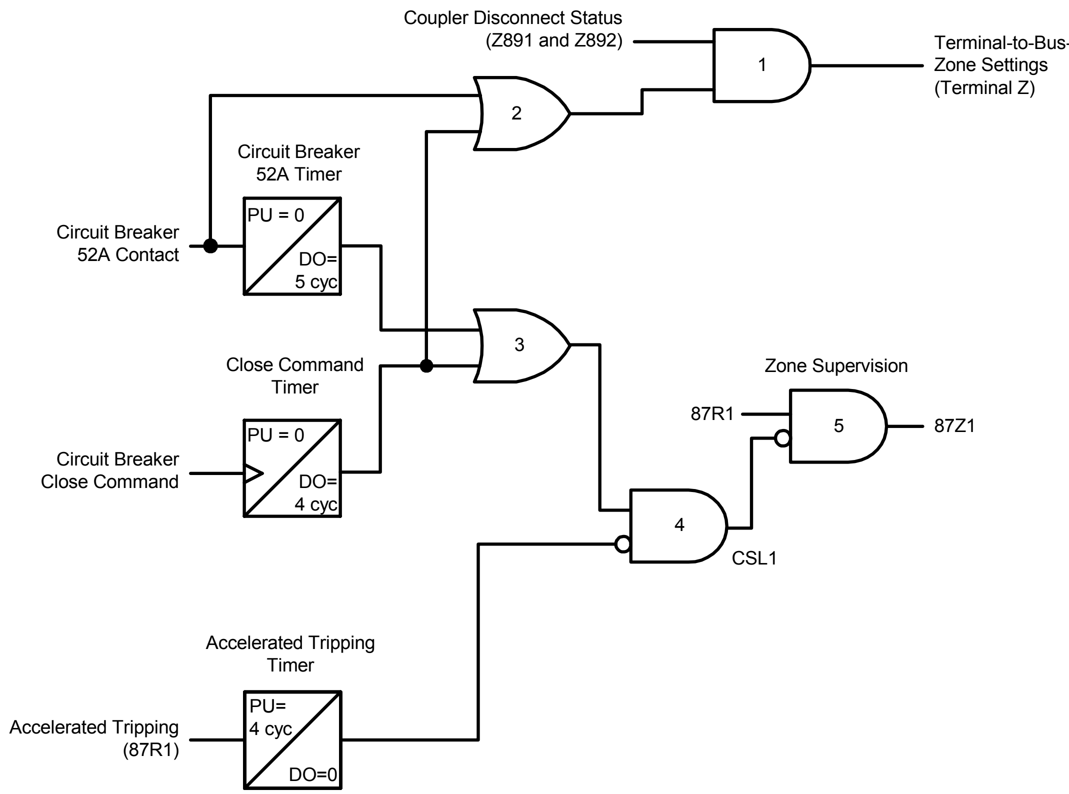


Figure 42 Combination of Coupler Security Logic and Zone Supervision to Prevent Loss of Two Zones

To prevent tripping of Zone 1 for Fault F1, configure the relay according to the following:

1. Check to see if the tie breaker is closed. If the tie breaker is closed, trip only the tie breaker to interrupt the fault current from Zone 1; trip no other circuit breakers. If the tie breaker is open, allow normal busbar protection tripping.
2. When the tie breaker is open, remove the tie-breaker CT from the differential calculations of Zone 1 and Zone 2.

To check tie-breaker status and remove the CTs when the tie breaker is open, use the Circuit Breaker 52A Contact and the Circuit Breaker Close command (Gate 2) to assign the tie-breaker CTs to the differential elements when the disconnects are closed (Gate 1), i.e., the relay does not consider the CTs in the differential calculations when AND 1 deasserts.

To trip only the tie breaker for faults in Zone 1, you must do the following:

- Supervise the Zone 1 differential element
- Issue a trip signal to the tie breaker for faults in Zone 1

To supervise the Zone 1 differential element, we assign the negated output from the coupler security logic (CSL1) to the bottom input of Gate 5. We also assign 87R1, the unsupervised output from the Zone 1 differential element, to the Accelerated Tripping Timer input of the coupler security logic. Supervising the Zone 1 differential element in this way prevents tripping of all terminals in Zone 1, including the tie breaker. To issue a trip signal to the tie breaker for Zone 1 faults, include 87R1, the unsupervised output from Differential Element 1, in the tie-breaker trip equation.

Because Zone 1 differential elements operate for Fault F1 (87R1 asserts), we must maintain Zone 1 supervision for at least another 1.25 cycles (add a safety margin of 0.75 cycle) after the tie breaker opens to allow the differential elements to reset. Achieve this 1.25-cycle delay by setting the Accelerated Tripping Timer to at least 4 cycles. We remove the tie-breaker CTs from the differential element calculations of Zone 1 and Zone 2 immediately after the tie breaker opens. We remove the Zone 1 supervision 1.25 cycles later.

For Fault F1, Zone 1 operates, asserting 87R1. When 87R1 asserts, Accelerated Tripping Timer starts timing. Because of the Zone 1 zone supervision (NOT CSL1), 87Z1 cannot assert, and only the tie-breaker circuit breaker receives a trip signal.

Two cycles later, the tie breaker trips, interrupting the fault current contribution from Zone 1. Assume that the circuit breaker auxiliary contact changes state at the same time. When the auxiliary contact changes state, AND 1 deasserts, causing the relay to remove the tie-breaker CTs from the differential calculations for Zone 1 and Zone 2. Also, when the circuit breaker auxiliary contact changes state, the Circuit Breaker 52A Timer 5-cycle drop-off delay maintains a logical 1 to Gate 4, thereby keeping CSL1 asserted.

Although the tie-breaker circuit breaker is open, fault current still flows through the CT from Terminal F. However, because the tie-breaker circuit breaker is open, terminals connected to Zone 1 no longer contribute to Fault F1. Therefore, the Zone 1 differential elements are stable after removal of the tie-breaker CTs from the Zone 1 differential calculations. However, removal of the CTs from the Zone 2 differential elements unbalances Zone 2 (balancing current from the tie-breaker CT has been removed), and Zone 2 trips. Fault F1 now clears, through tripping of the correct zone, although after a time delay. Furthermore, removing the tie-breaker CTs also deasserts 87R1, causing the accelerated trip timer to stop timing.

For Fault F2, initial tripping is the same as for Fault F1: Zone 1 operates, asserting 87R1. When 87R1 asserts, the accelerated trip timer starts timing. Because of the Zone 1 zone supervision (NOT CSL1), 87Z1 cannot assert, and only the tie-breaker circuit breaker receives a trip signal. Two cycles later, the tie breaker trips, and the auxiliary contact changes state at the same time. When the auxiliary contact changes state, AND 1 deasserts, causing the relay to remove tie-breaker CTs from the differential calculations for Zone 1 and Zone 2. Because the tie-breaker circuit breaker is open, terminals connected to Zone 2 no longer contribute to the fault and Zone 2 is stable. No tripping takes place for another 2 cycles, because the Zone 1 zone supervision (NOT CSL1) still supervises the Zone 1 trip output. Two cycles later, Accelerated Trip Timer expires, causing CSL1 to deassert, removing zone supervision from Zone 1. With the zone supervision removed, the relay issues a trip signal to all circuit breakers in Zone 1. Fault F2 now clears, through tripping of the correct busbar, although after a time delay. Here, the tradeoff is the cost of three CTs versus delayed fault clearance and the loss of both zones.

Table 7 summarizes the results of Fault F1 for all three tie-breaker configurations.

Table 7 Configuration Comparison

CT Configuration	Cost	Clearing Time	Zones Lost
2 CTs, overlap	highest	fastest	2
2 CTs, differential	highest	slower	1
Single CT	lower	slowest	2/1[2]

Table 8 shows the various tie-breaker applications and the types of plants in which the applications are most likely to be installed.

Table 8 Typical Bus Section Application Categories

CT Configuration	Application
2 CTs, overlap	Power plants, or installations where delayed tripping may result in system instability.
2 CTs, differential	Stations with 2 zones only, but for high-profile customers. Stations of strategic importance.
Single CT	Remainder of stations.

These applications are not new, and busbar protection relays have been protecting these applications for many years. However, the busbar protection relay this paper discusses protects any one of the three applications without additional wiring or auxiliary relays. One configures the relay through simple software configuration settings.

End-Zone (Stub) Protection

Configure other related protection such as end-zone protection with the flexible programming feature of the system. For example, Figure 43 shows Fault F1, a fault between the feeder CT and circuit breaker called the end-zone, or stub. The busbar protection at Busbar S operates for this fault and trips Circuit Breaker 1, but the line still feeds the fault from the source at Busbar R.

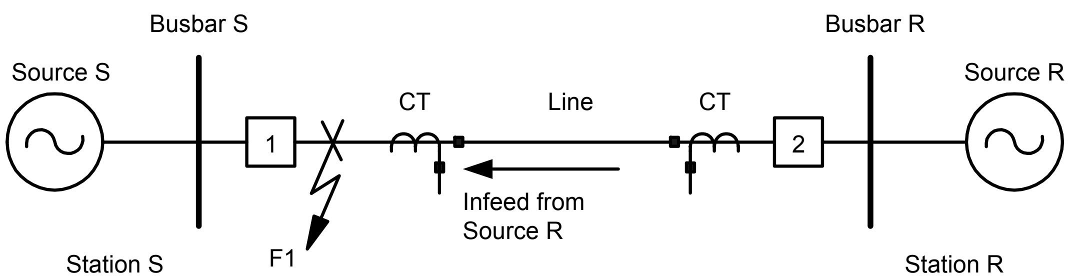


Figure 43 Fault Between Circuit Breaker 1 and the CT at Busbar S

Fault F1 clears only when Circuit Breaker 2 at Busbar R trips. In step-distance protection schemes, Circuit Breaker 2 trips after a time delay, typically on the order of 400 ms. Using end-zone protection, we can shorten the delay by sending a direct transfer trip (DTT) from Station S

[2] Using the logic in Figure 42

to Circuit Breaker 2 at Station R to trip Circuit Breaker 2. One way to identify an end-zone fault is when the following conditions are true:

- The circuit breaker is open.
- Current still flows in the CT.

On receipt of the DTT from Station S, the relay at Station R trips Circuit Breaker 2 and clears the fault in about 5 cycles. Other protection philosophies may declare an end-zone fault under different conditions; as we stated before, a busbar protection relay must be flexible enough to accommodate a wide range of applications.

Zone Supervision

Zone supervision provides control equations that specify conditions to supervise the differential element, as shown in Figure 44. In Figure 44, the top input into the AND gate is the trip output from the differential element. This input asserts when the relay operates for a busbar fault. However, most protection philosophies call for other criteria to supervise the differential element before the relay issues the final trip signal. Examples include supervision through use of disconnect status and other digital input information available in the protected station.

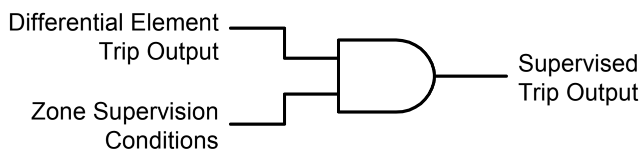


Figure 44 Zone Supervision Logic

For protection philosophies in which a check zone must be a second trip criterion, we can specify the check zone as a zone supervision condition. Specification of the check zone as a zone supervision condition effectively combines check-zone differential elements and zone-specific differential elements within one relay.

Back-Up Overcurrent

Back-up overcurrent protection for each terminal is another benefit of having the current input from each terminal and a trip signal to the trip coil of each terminal available in one location. Centralized back-up overcurrent would be ideally suited to distribution-level stations. Normally, the trip signal of the busbar protection relay is in parallel with the trip signal of the protection relay on the terminal panel. Wiring in this fashion provides backup overcurrent protection from the overcurrent elements in the busbar protection relay, should the terminal protection relay fail.

Differential and Breaker Failure Protection Performance

The proposed busbar and breaker protection scheme has been implemented in a microprocessor-based relay that provides differential and station-wide breaker failure protection for single bus, double bus, double bus with transfer, breaker-and-a-half, triple bus arrangements, generators and motors, shunt capacitor banks, autotransformers, and reactors. Many tests have demonstrated the ability of the relay to provide fast operating times for all busbar faults (Figure 45 and Figure 46), security for external faults with heavy CT saturation (Figure 47), and minimum delay for evolving faults (Figure 48). The only requirement is that the relay must work with primary CTs that reproduce primary current without saturation for at least 2 ms after external fault inception. In test cases, the relay has provided fast operation for high fault currents, low fault currents, and external-to-internal evolving faults. For external faults, the relay was secure even with severe CT saturation and heavy subsidence current presence. The system in Figure 49 shows an external fault condition that the feeder breaker clears properly. Figure 50 shows that the faulted feeder CT saturates during the external fault condition. After the breaker opens to clear the fault, the CT continues to inject heavy subsidence current to the relay, as Figure 50 illustrates. The differential scheme maintains its security for this condition because of the filtered differential element supervision.

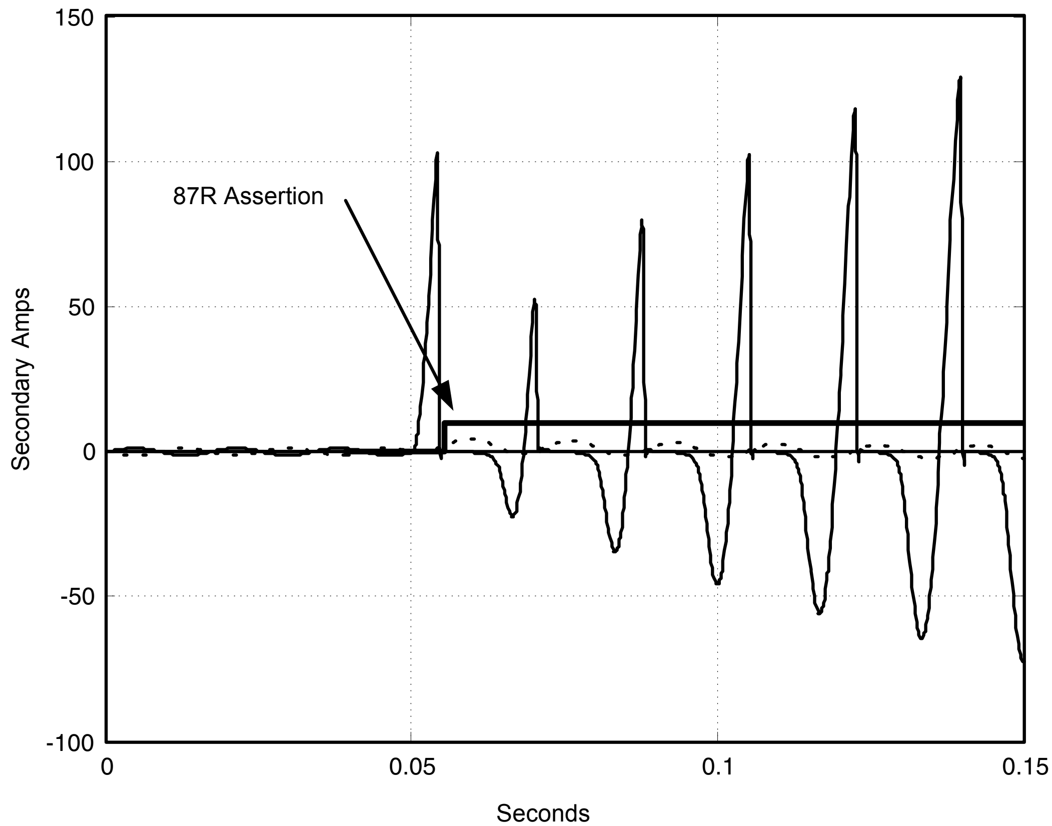


Figure 45 Fast Operating Times for an Internal Busbar Fault

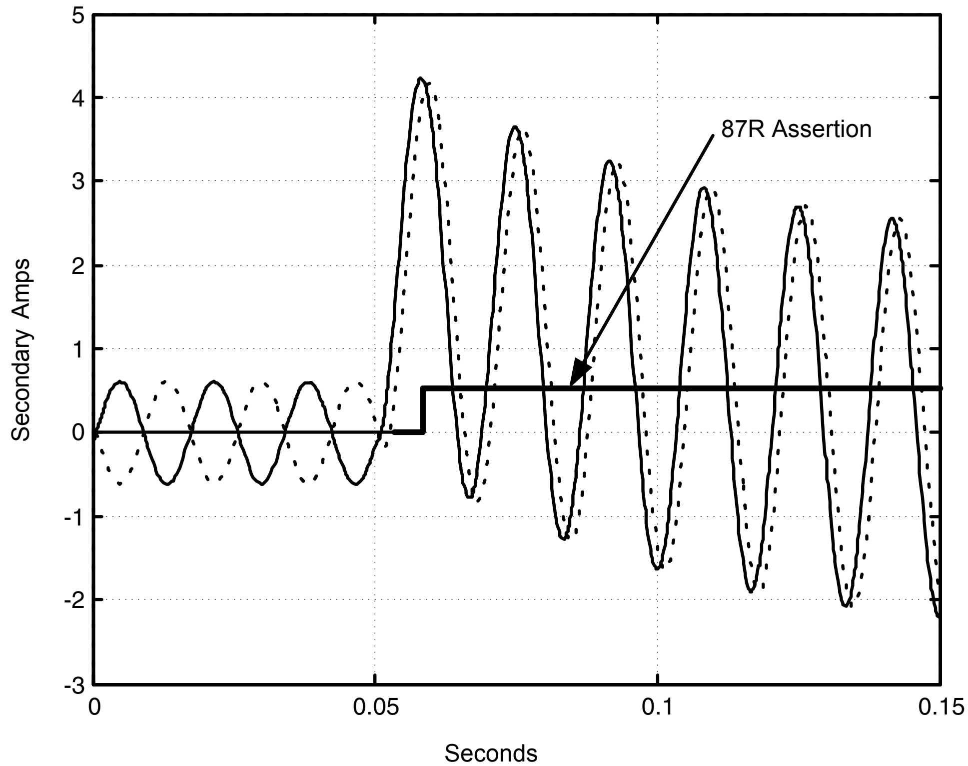


Figure 46 Fast Operating Times for Low Current Faults

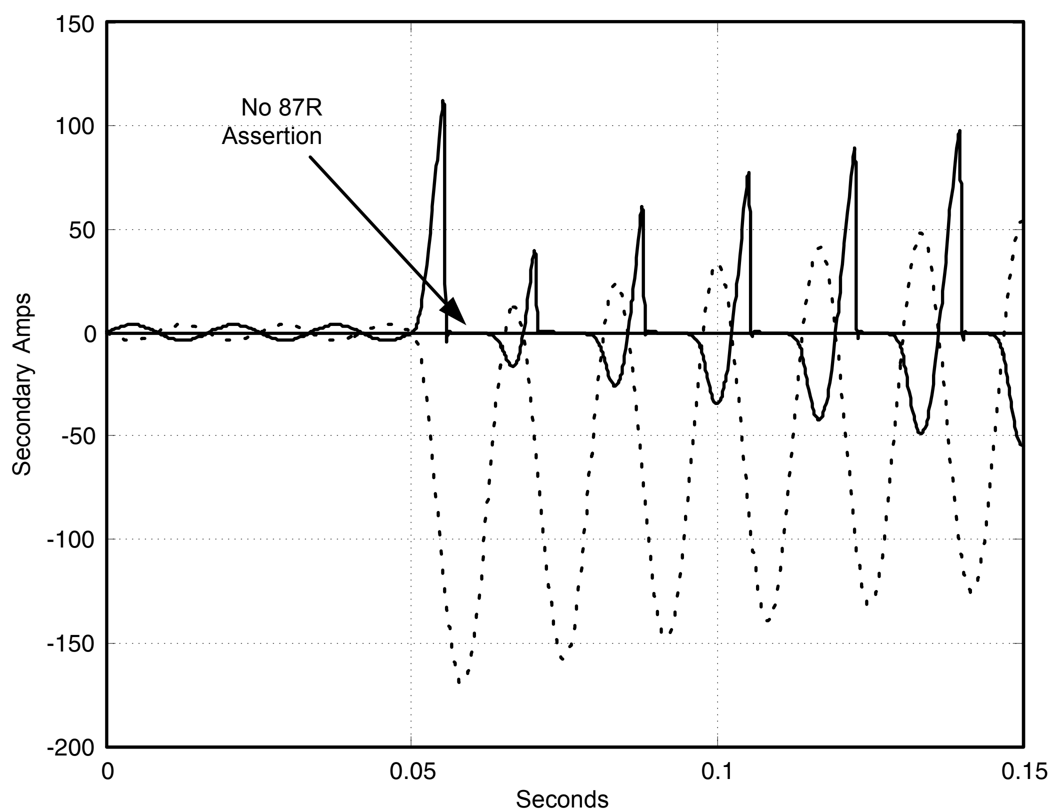


Figure 47 Security for External Faults With Heavy CT Saturation

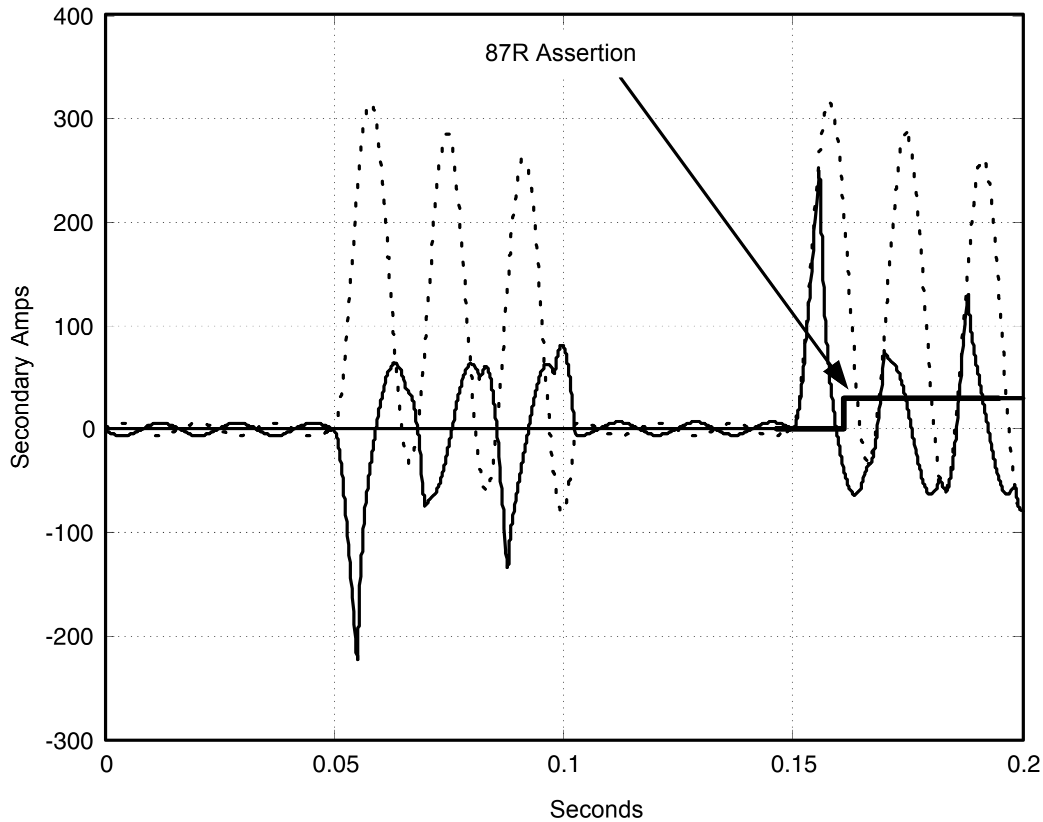


Figure 48 Fast Operating Times for Evolving Faults

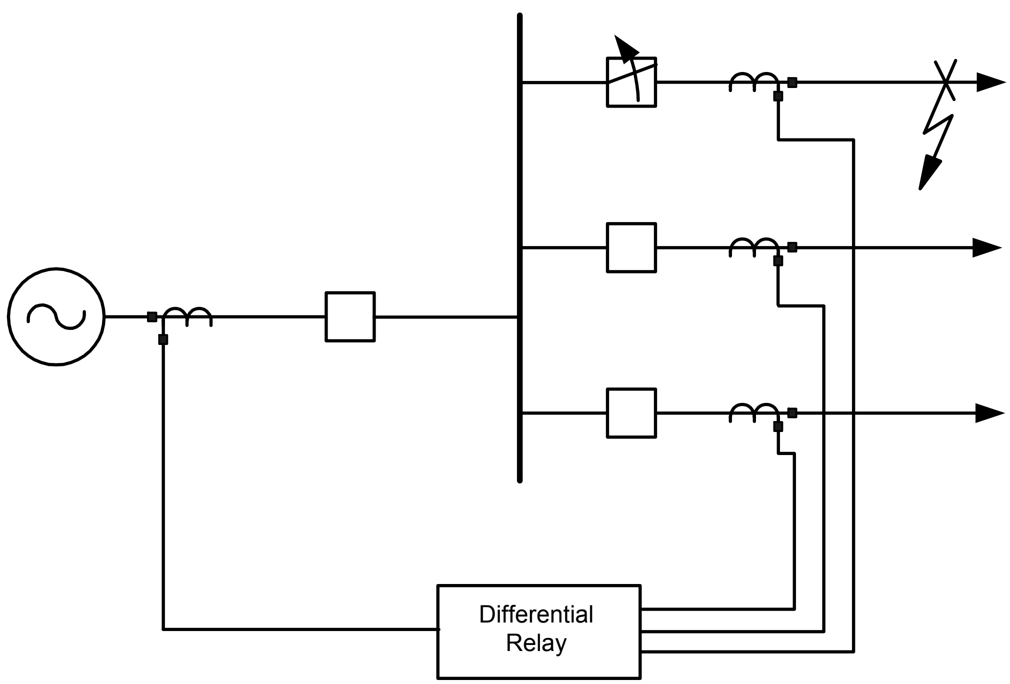


Figure 49 External Fault Causes Faulted Feeder CT to Saturate. Subsidence Current Continues to Flow in the Secondary Circuit After the Breaker Opens

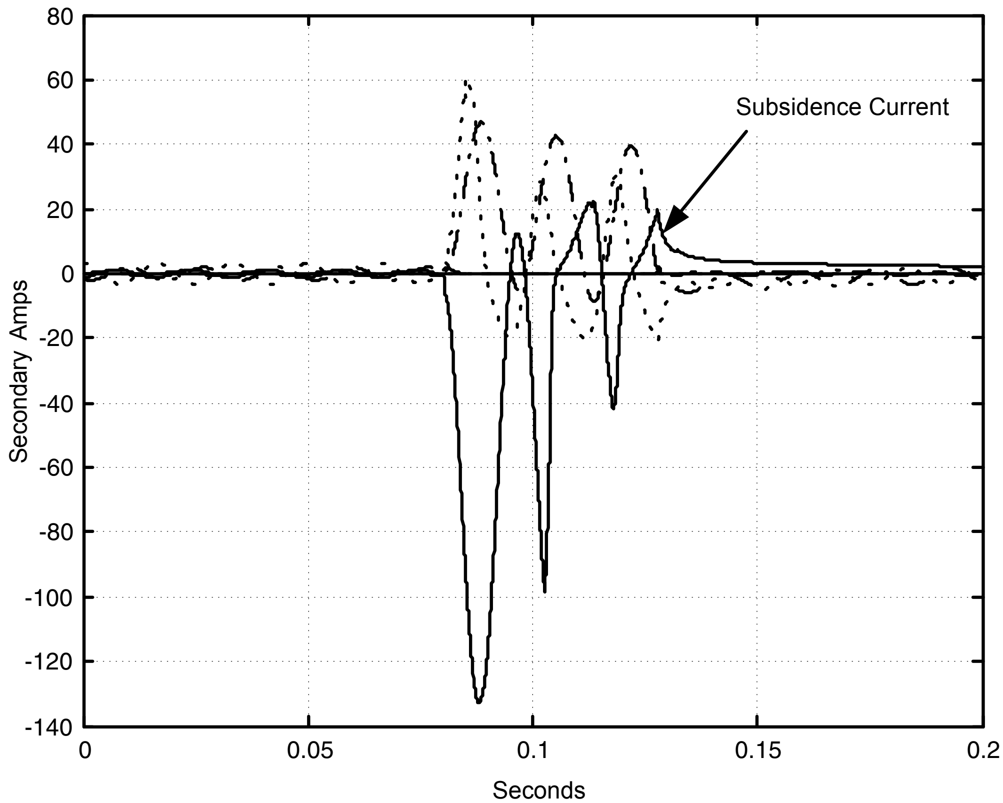


Figure 50 Filtered Differential Element Supervision Provides Security in the Presence of Subsidence Current

Fault resistance compromises the dependability of differential elements that are supervised with directional elements. Figure 51 shows a 400 kV busbar fault with a 20 Ω fault resistance. In this case, the internal fault detection logic operates in less than one cycle to clear the fault, while the directional element did not operate (Figure 52).

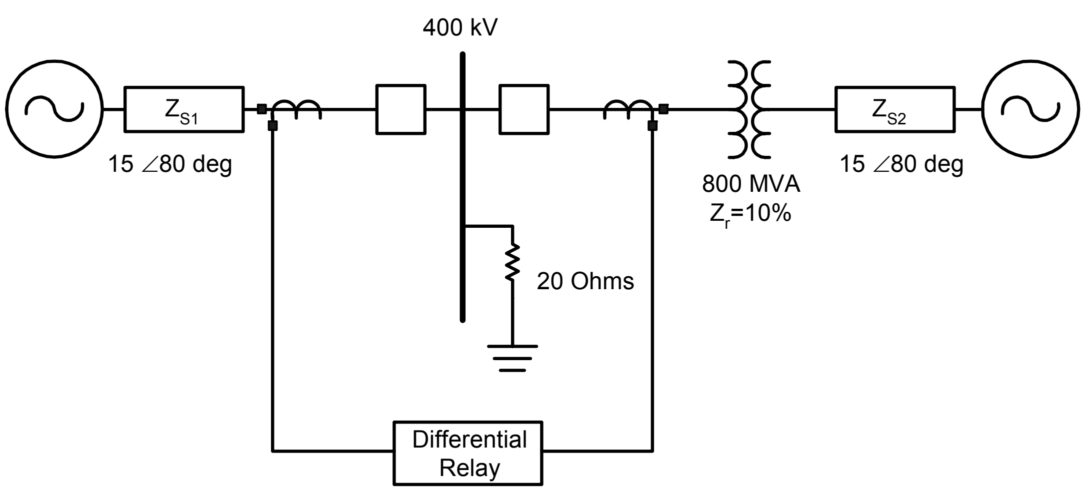


Figure 51 400 kV Busbar Fault With 20 Ω Fault Resistance

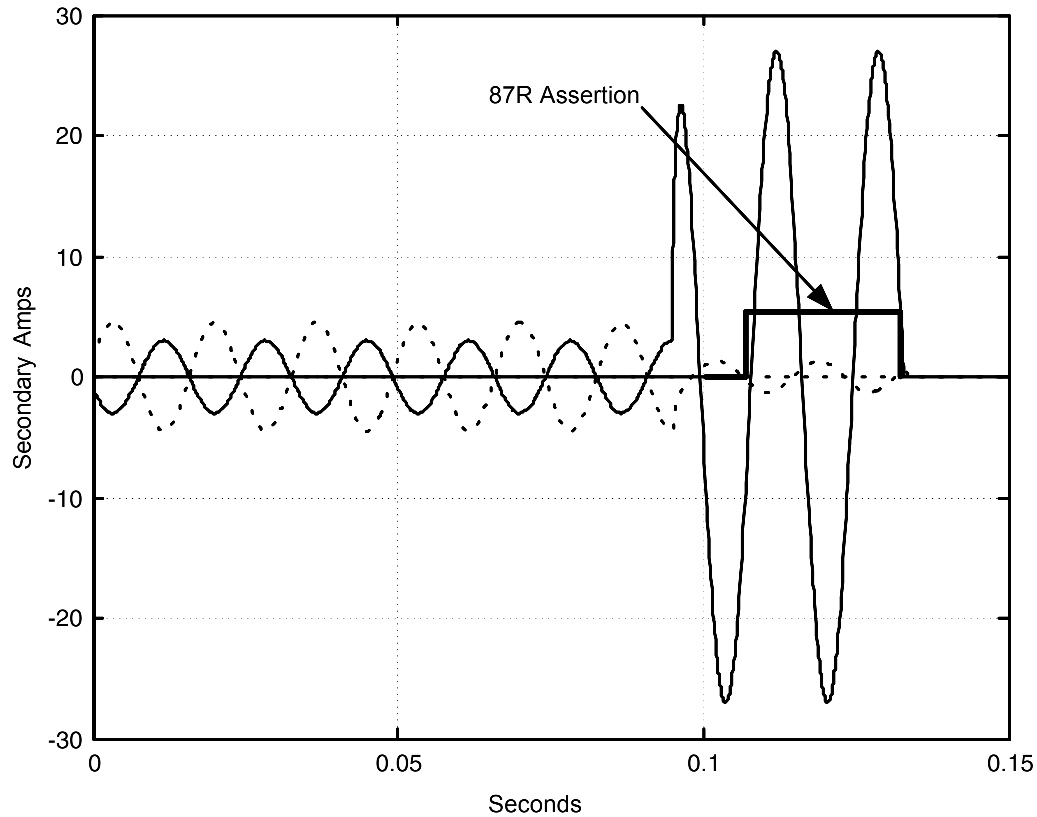


Figure 52 Internal Fault Detector Is More Dependable Than the Directional Element

For external faults, the relay is secure even with severe CT saturation, while providing sub-cycle resetting of overcurrent elements in the presence of subsidence current. Sub-cycle resetting times allow smaller breaker failure protection coordination margins. Figure 53 shows that the open-phase detector, described earlier, detects an open-phase condition in less than one cycle. The open-phase detector detects the open-phase condition faster than overcurrent elements that use half-cycle or full-cycle filtering windows.

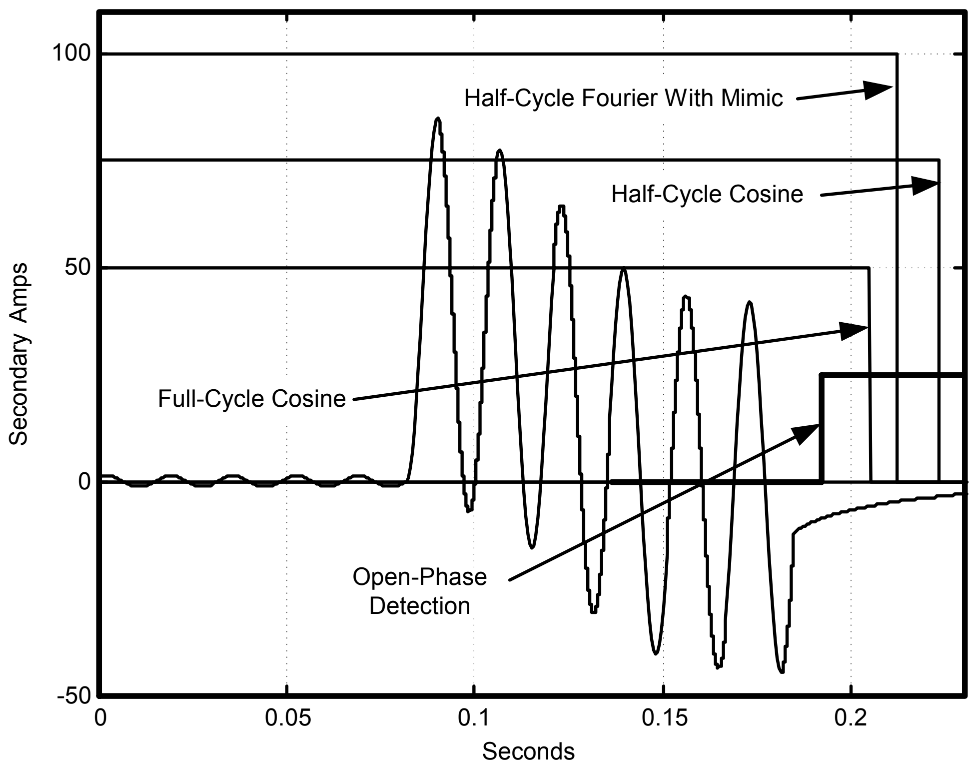


Figure 53 The Open-Phase Detector Detects the Open-Phase Condition in Less Than One Cycle. It Detects the Open-Phase Condition Faster Than Overcurrent Elements That Use Half-Cycle or One-Cycle Filtering Windows.

CONCLUSIONS

1. Dynamic zone selection assigns current inputs dynamically to the correct differential element(s). Instead of disabling bus protection during disconnect switching, use zone selection to provide bus protection during switching operations, when the safety of personnel is at high risk.
2. When a protection philosophy calls for an overall check zone, any protection zone can be configured as a check zone.
3. A second trip criterion is incorporated into each of the protection elements. This criterion consists of the logic OR combination of a directional element in parallel with a fault detection element.
4. Innovative differential protection switches the relay to a high-security mode during through-fault conditions. While in the high-security mode, the algorithm does not block the differential elements, thus avoiding unnecessary time delays for clearing faults evolving from external to internal faults.
5. The type of breaker failure protection (internal or external) is selectable on a terminal-by-terminal basis. Internal breaker failure protection provides breaker failure trip and breaker retrip for all terminals. Open-phase detection ensures current-element reset in less than a cycle. For external breaker failure protection, select the external breaker failure option. With this option, the relay accepts inputs from breaker failure relays installed in feeder protection panels.

6. A unique combination of multiple protection principles allows the integration of station-wide protection (busbar and breaker failure protection) into one relay. One relay provides end-zone protection and backup overcurrent protection. The same relay is suitable for diverse tie-breaker protection applications without the need for auxiliary relays or additional wiring.
7. Integrated busbar and breaker failure protection minimizes panel wiring and avoids duplication of common functionality. The result of this integrated approach is a more reliable and more economical scheme.

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BIOGRAPHIES

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