



IEEE Guide for Protective Relay Applications to Power System Buses

IEEE Power & Energy Society

Sponsored by the
Power System Relaying Committee

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IEEE Guide for Protective Relay Applications to Power System Buses

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Power System Relaying Committee
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IEEE Power & Energy Society

Approved 11 September 2009

IEEE-SA Standards Board

Abstract: Concepts of power bus protection are discussed in this guide. Consideration is given to availability and location of breakers, current transformers, and disconnectors as well as bus-switching scenarios, and their impact on the selection and application of bus protection. A number of bus protection schemes are presented; their adequacy, complexity, strengths, and limitations with respect to a variety of bus arrangements are discussed; specific application guidelines are provided. Breaker failure protection is discussed as pertaining to bus protection. Means of securing bus protection schemes against corrupted relay input signals are also included.

Keywords: breaker-and-a-half, breaker failure (BF) protection, breaker substitution, buses, check zone, CT saturation, current transformers, differential bus protection, double-bus double-breaker, double-bus single-breaker, dynamic bus replica, electric power substations, high-impedance differential, main bus, partial differential, percentage differential, protective relaying, ring bus, single-bus single-breaker, stub bus, transfer bus, voltage trip supervision, zone-interlocked bus protection

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Introduction

This introduction is not part of IEEE Std C37.234-2009, IEEE Guide for Protective Relay Applications to Power System Buses.

Electric power system buses are points of common connection for source and load circuits. As such buses are essential in maintaining power system integrity. Unnecessary isolation of a power bus by its protection system can considerably alter topology of the power grid and, even without other contingencies, can lead to system stability problems. Therefore the security of bus protection schemes is of paramount importance.

At the same time the close proximity and connection of various power apparatus within the perimeter of a substation and its exposure to secondary effects of a short circuit require fast isolation of all bus faults.

This document provides application guidelines for selecting and engineering bus protection schemes for a variety of bus configurations using several different protection philosophies to meet the requirements of security, dependability, and speed of operation.

The guide reviews many typical bus configurations and explains typical switching operations and their impact on the bus protection systems. This includes reconfigurable buses, such as double-bus single-breaker configuration, breaker substitution, main and transfer bus, etc., where the zones of protection change as the bus is switched, thus requiring the bus protection system to adapt accordingly for optimum selectivity.

The document reviews the most common bus protection schemes and presents their relative advantages given specific bus configuration and switching flexibility, as well as performance requirements for the protection system. This includes schemes ranging from differentially connected overcurrent relays to microprocessor-based differential schemes with dynamic zone selection.

After reviewing relay input sources—current transformers (CTs), voltage transformers (VTs), and position sensing schemes for breakers and disconnect switches—the guide elaborates on each bus protection method in more detail by examining the operating principle, providing general setting guidelines and listing general requirements for CTs.

The document also discusses specific related bus protection application issues including, but not limited to, partial differential protection, applications with paralleled CTs, CT column ground fault protection, voltage trip supervision, dynamic bus selection for double-bus single-breaker buses, bus protection under a breaker substitution configuration, stub bus configuration or configuration with paralleled buses, breaker failure (BF) application for reconfigurable buses, and treatment of in-zone out-of-service elements that provide a ground path for short-circuit currents.

A setting calculation example for a high-impedance bus differential scheme is given in Annex A.

A protection logic design example is provided in Annex B to illustrate concepts of dynamic zone selection, dynamic BF trip selection, protection during a breaker substitution configuration, or circuit transfer leading to paralleling multiple buses via disconnect switches, voltage trip supervision, and the check zone. The example has been developed for a double-bus single-breaker configuration, but these advanced bus protection concepts are applicable to any reconfigurable bus.

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1. Overview

1.1 Scope

Concepts of power bus protection are discussed in this guide. Consideration is given to availability and location of breakers, current transformers (CTs), and disconnectors, as well as bus-switching scenarios, and their impact on the selection and application of bus protection. A number of bus protection schemes are presented; their adequacy, complexity, strengths, and limitations with respect to a variety of bus arrangements are discussed; specific application guidelines are provided. Breaker failure (BF) protection is discussed as pertaining to bus protection. Means of securing bus protection schemes against corrupted relay input signals are also included.

1.2 Purpose

The purpose of the guide is to assist utility engineers and industrial and commercial plant engineers in selecting and engineering proper bus protection.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std C37.2™, IEEE Standard for Electrical Power System Device Function Numbers, Acronyms, and Contact Designations.^{1, 2}

IEEE Std C37.110™, IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes.

IEEE Std C37.119™, IEEE Guide for Breaker Failure Protection of Power Circuit Breakers.

IEEE Std C57.13™, IEEE Standard Requirements for Instrument Transformers.

IEEE Std C57.13.3™, IEEE Guide for Grounding of Instrument Transformer Secondary Circuits and Cases.

3. Definitions

For the purposes of this document, the following terms and definitions apply. *The IEEE Standards Dictionary: Glossary of Terms & Definitions* should be referenced for terms not defined in this clause.³

Definitions of several terms used in this guide are provided in IEEE Std C37.100™-1992 [B17].⁴

blind spot: In bus protection, the area between the circuit breaker and its associated current transformer(s) on network elements or bus tie breakers where the CTs have only been installed on one side of the circuit breaker; faults in such blind spots will not be cleared instantaneously by the bus protection.

breaker substitution: Temporary usage of a bus tie breaker in a multiple bus configuration to substitute for one of the network element's circuit breakers, typically for the maintenance of the latter; also known as *breaker transfer*.

breaker-and-a-half: A substation configuration wherein two main buses are bridged by two or more "diameters," each diameter consisting of three circuit breakers in series, with a circuit or other element tapped at each of the two junctions between the circuit breakers. A variation has four circuit breakers and three circuits per diameter.

bus: A portion of a switchyard or a switchgear that electrically interconnects a number of circuit breakers and switches, and is protected as a separate entity from network elements. It may also directly connect other elements such as grounding transformers without breakers/switches.

bus section: A contiguous portion of a bus, able to be electrically disconnected from other sections of the bus.

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³ *The IEEE Standards Dictionary: Glossary of Terms & Definitions* is available at <http://shop.ieee.org/>.

⁴ The numbers in brackets correspond to those of the bibliography in Annex D.

bus-side CT: Current transformer located between the circuit breaker and the bus.

check zone: Nonselective part of a multi-zone bus protection system measuring current flows around the entire station and supervising selective tripping from individual bus zones of protection.

CT column ground fault protection: A method of ground fault protection for a freestanding current transformer or a live-tank breaker.

CT trouble detection: A monitoring function of a bus protection system capable of detecting differential current that is not caused by a bus fault.

diameter: One of several connecting circuits between buses in a double bus-double breaker or breaker-and-a-half substation configuration; also referred to as a *bay* or *breaker bay*.

double-bus double-breaker: A substation configuration having two breakers per each circuit where each of the breakers is connected to a separate bus.

double-bus single-breaker: A substation configuration having one breaker per each circuit where each of the breakers is connected to a separate bus via a disconnect switch.

dynamic bus replica: A mechanism of dynamically tracking connections to or within the protected bus by monitoring positions of disconnect switches, and in rare cases, circuit breakers; for example, maintaining optimum selectivity of protection by dynamically associating CTs and circuit breakers to a multitude of bus protection zones.

freestanding CT: Current transformer independent of other apparatus.

high-impedance scheme: A differential method of bus protection using CTs paralleled on a high-impedance load (a voltage or current relay in series with a stabilizing resistor).

line-side CT: A current transformer located on the far side of a breaker from the bus.

network element: Any electrical device or set of electrical devices (e.g., a line, feeder, transformer, capacitor bank, generator), operated as a unit and connected to a bus via a circuit breaker. In figures, a network element is indicated symbolically by a line with an arrow head.

over-tripping spot: In bus protection, an area within the bus protection measuring zone that is, or can be, electrically isolated from the bus by a circuit breaker or disconnect switch, such as where using a line-side CT for bus protection; will result in unnecessary bus trip should a fault occur in such a location.

ring bus: A substation configuration with a series connection of breakers or switches closing back on itself, to form a ring, with a circuit or other element tapped at each of the junctions between the circuit breakers/switches.

stub bus: Area of a bus or line that becomes isolated from the original zone of protection or an area that loses protection due to the loss of sensing to zone protection relays.

tie breaker: A circuit breaker connecting two buses; also known as a *bus coupler* or a *sectionalizing breaker*.

voltage trip supervision: A supervisory function that responds to undervoltage or voltage unbalance conditions, which is used to secure current-based bus protection schemes from problems associated with temporary or permanent abnormal current readings.

4. Buses in various station arrangements

There are a number of considerations in designing a bus:

- a) Reliability requirements in terms of continuity of service for the bus as a whole or for an essential network element supplied from the bus.
- b) Operational considerations in terms of equipment maintainability and network switching flexibility.
- c) Economical and footprint constraints.
- d) Sectionalizing requirements to avoid exceeding breaker fault duty and operational cycles.
- e) Ease of future bus expansion.

It is essential to understand the various bus arrangements before selecting an adequate protection scheme for a given bus configuration.

There are six major bus configurations in common use, as follows:

- Single bus
- Main and transfer bus
- Double-bus double-breaker
- Double-bus single-breaker
- Breaker-and-a-half
- Ring bus

These classical bus arrangements are described and discussed in the following subsections. In the included figures not all CTs and disconnect switches are depicted, only those that pertain to bus protection.

4.1 Single bus

With reference to Figure 1, the single bus configuration (also known as *straight bus* or *single-bus single-breaker*) consists of a single bus with all network elements connected directly with breakers. This configuration is simple and economical. However, from the system point of view it is the least reliable and least flexible in terms of network switching and equipment maintenance.

Note that this document depicts CTs, wiring, and relay devices in a simplified manner, for explanation of bus protection methods and applications; refer to IEEE Std C57.13.3 for rules of grounding secondary CT and relay circuits.⁵

All network elements in the single bus configuration are taken out of service upon a bus fault or for bus maintenance. Maintenance or problems with a given breaker call for taking its associated network element out of service. Under a BF condition, the entire bus is cleared.

From the protection point of view, the measurement zone of protection for the single bus configuration is bounded by CTs on all the connected network elements, and all the connected breakers are tripped upon a bus fault. Figure 1 shows a desired situation with CTs available on both sides of each breaker, allowing the bus measurement zone and the measurement zones of protection of the network elements to overlap thus

⁵ Information on references can be found in Clause 2.

eliminating any blind spots. Live tank breakers with freestanding CTs located on only one side do not provide for such overlap and therefore are treated with extra considerations, as described in 8.12.

Often to increase reliability and reduce breaker fault duty requirements, a single bus is split into—typically two—sections with a switching device (tie) between them. The multiple sections are preferably supplied from multiple sources with some degree of independence.

With reference to Figure 2(a), the tie can be a breaker rated for fault current interruption. In this case, a preferable arrangement is to install CTs on both sides of the tie breaker (TB) so that two independent zones of bus protection can be applied to protect and trip both the bus sections independently. Upon a fault on zone 1 all network elements connected to zone 1 and the tie breaker are tripped. Upon a fault in zone 2 all its network elements are tripped as well as the tie breaker. For faults between the tie breaker and its CTs both buses are tripped unless special means are deployed to pinpoint the fault better and save one of the bus sections. Typically, these methods are based on intentionally delayed tripping and are better described in 8.12.

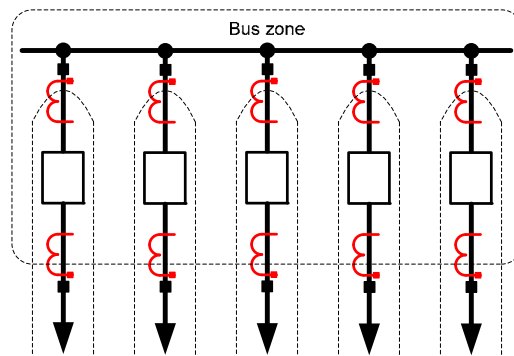


Figure 1—Single bus configuration

Under BF conditions upon a fault on any network element, only the connected bus section is tripped including the tie breaker. This allows uninterrupted service of network elements connected to the other section.

In some configurations the tie breaker is equipped with CTs on one side only [Figure 2(b)]. This case requires careful protection engineering to deal with the blind spot between the TB and the CT. Detailed solutions to this problem are presented in 8.12.

When the bus tie is not a properly rated breaker, but a disconnect, the bus may be operated with the disconnect open (typically) or closed (occasionally) as shown in Figure 3(a) and Figure 3(b), respectively.

With the disconnect open, this bus configuration becomes two independent single buses and is protected as such with two independent bus protection schemes. When the disconnect switch is closed, the two bus sections cannot be separated under a bus fault condition as the tie switch does not have sufficient fault interrupting capabilities. Therefore, the entire bus structure is protected as a single bus.

When the bus tie is a disconnect switch, there is no need for current measurement at the tie, and therefore no CTs are typically installed. Instead, the disconnect position becomes an important input to the bus protection scheme controlling which currents are included in the zones of protection, which breakers are tripped under bus faults and under BF conditions.

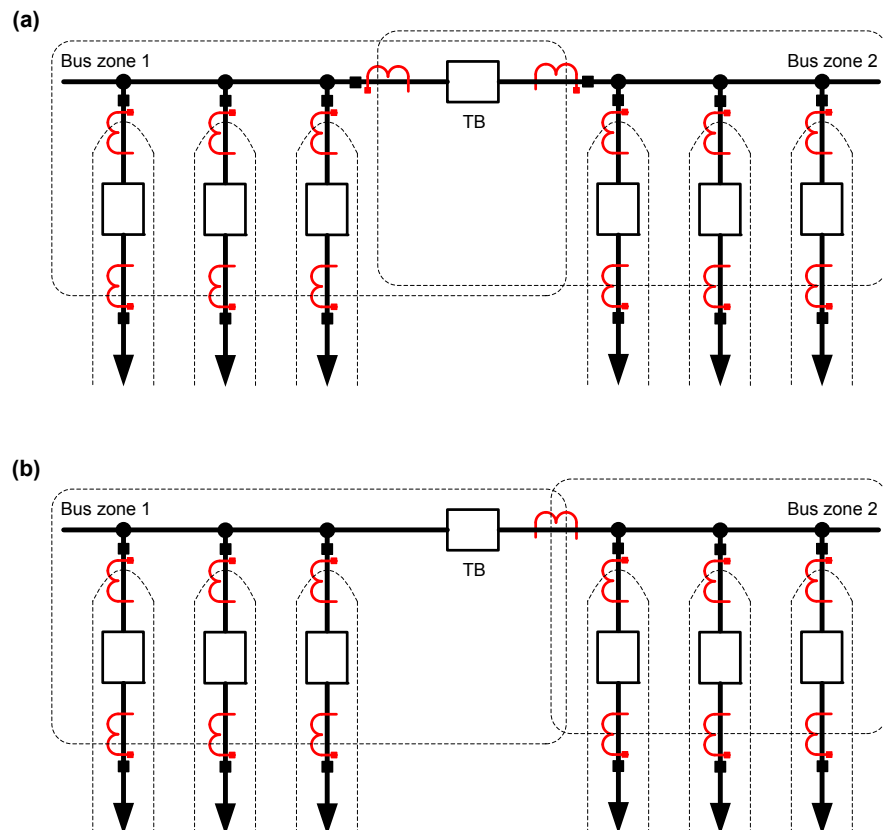


Figure 2—Single bus sectionalized with a tie breaker: current transformers on both sides (a), and on one side of the tie breaker only (b)

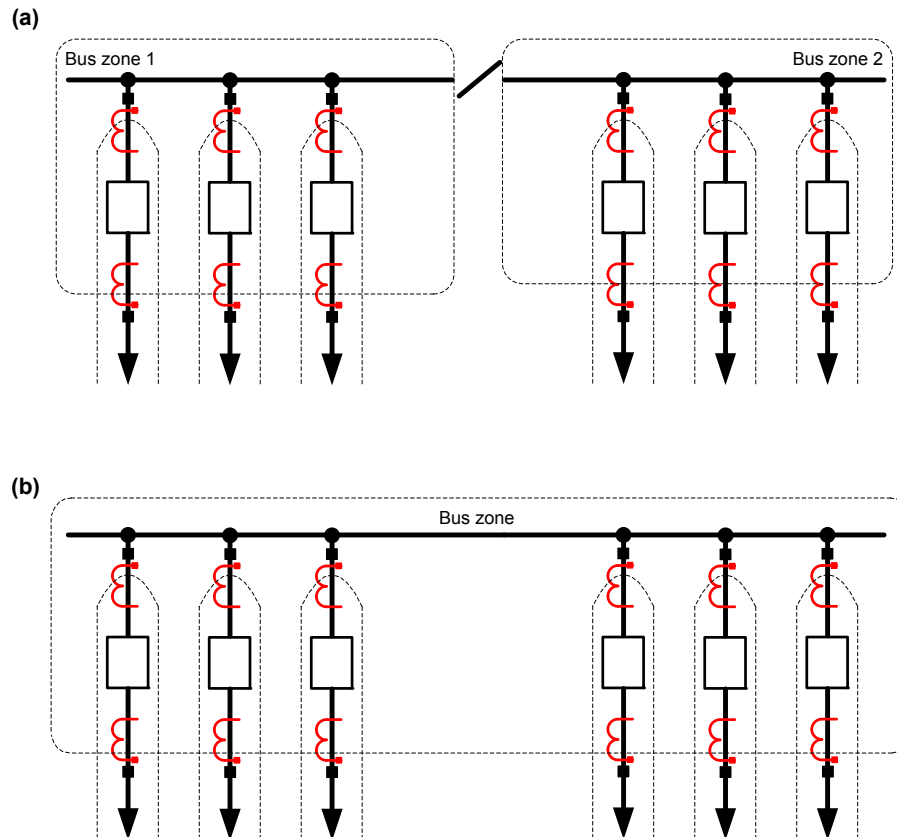


**Figure 3—Single bus sectionalized with a disconnect switch:
bus protection with the disconnect open (a), and closed (b)**

4.2 Main and transfer bus

This bus configuration is an extension of the single bus arrangement and is aimed at bringing extra equipment maintenance and switching flexibility without adding extra breakers. In reference to Figure 4, a second bus, called a *transfer bus* or an *auxiliary bus*, is added to the single bus configuration. Each network element is connected to the main bus via a breaker, and to the transfer bus via a disconnect switch. An extra breaker, called a *bus tie* (TB), or a bus coupler is inserted between the main and transfer buses.

Normally, all network elements in this configuration are supplied from the main bus, and the bus tie is opened leaving the transfer bus de-energized. When a breaker is to be maintained, the associated network element is supplied from the transfer bus via the disconnect switch, while the transfer bus is fed via the bus tie. In this way the network element is transferred to the bus tie breaker, hence the “transfer bus” designation. During the transfer, the network element is protected by the transfer breaker. As a result the bus tie acts as a substituting breaker, and the transfer bus is temporarily included in the zone of protection of the transferred network element (Figure 5).

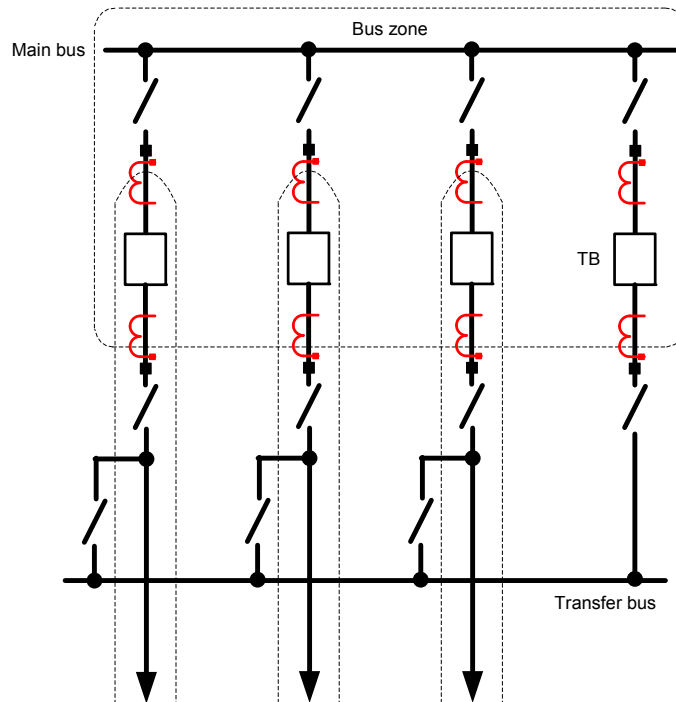


Figure 4—Main and transfer bus configuration

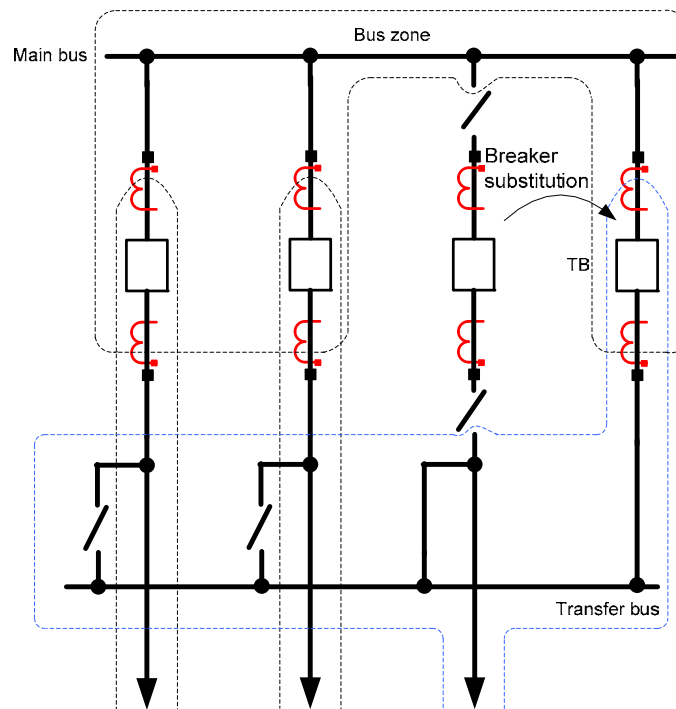


Figure 5—An example of a network element transferred to the bus tie breaker

From the bus protection point of view, this arrangement is as simple as the single bus. Only one zone of bus protection is required and spans CTs and breakers of all network elements and the bus tie breaker.

From the point of view of protecting the network elements, extra complexity arises from the requirement of routing the current and trip signal paths from the main breaker to the substituting bus tie breaker. This may be accomplished by manually switching the signal paths, or by using an extra relay at the tie and temporarily reprogramming it to serve as the main protection for the transferred network element.

4.3 Double-bus double-breaker

This bus configuration provides for both reliability and operational flexibility at the expense of using two circuit breakers per each network element, hence the designation *double-breaker*. Two bus sections are set up and connected via diameters of two breakers. Each of the network elements is supplied from two breakers in each diameter as shown in Figure 6.

In this configuration a failure or maintenance of one bus section does not interrupt service to any of the network elements; a problem or maintenance of a breaker does not require taking the connected network element out of service.

From the point of view of protection of the network elements, two sets of CTs are connected to the protection scheme in order to bound a zone of protection (CT summation or dual-CT-input relays), and two breakers are tripped to isolate a fault on the network element. The increased number of breakers elevates the probability of a BF situation.

Upon a BF condition for tripping a network element fault, the entire bus section is cleared. This, however, does not interrupt service to any other of the network elements.

Bus protection is simple for this bus configuration. Two independent bus zones are used to cover the two bus sections. Upon a bus trip and BF condition, the other breaker in the diameter is tripped. In this way the healthy bus section always remains in service.

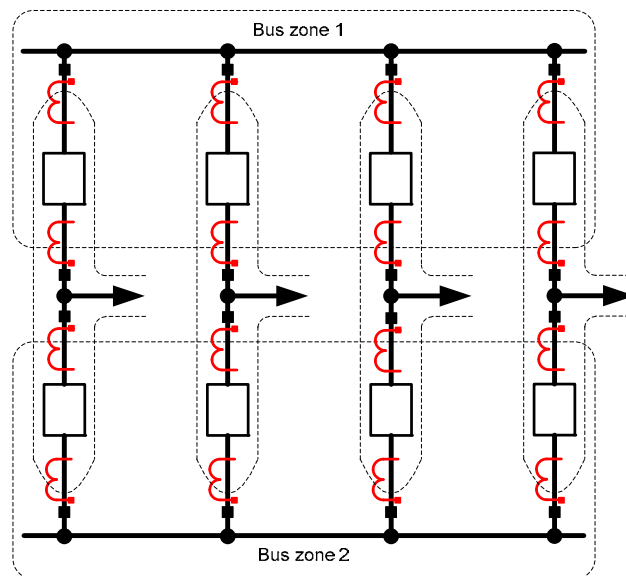


Figure 6—Double-bus double-breaker configuration

4.4 Double-bus single-breaker

This configuration delivers a good compromise between reliability and flexibility on the one hand, and the footprint requirements and economical factors on the other. This is at the expense of more complicated bus protection schemes.

In reference to Figure 7 each network element is connected via a single-breaker (hence the designation *single-breaker*), but can be routed to either of the two bus sections via a disconnect switch. A bus tie breaker is often used in this configuration to connect the two buses.

At any given time each network element is connected to one bus section only, except during transfers between the buses. The tie breaker is used to equalize potentials between the two buses, before transferring a given network element from one bus section to the other.

From the point of view of protection of network elements, this configuration calls for a straightforward single-breaker application as in the case of a single bus.

For maximum selectivity, bus protection is deployed with two zones of protection for each of the bus sections. However, the zone boundaries change depending on which network element is connected to which bus section. For this application the bus protection scheme dynamically assigns currents to its measurement zones and dynamically selects breakers to be tripped. This capacity is referred to as *dynamic bus replica* and is described in 8.8.

When transferring a network element between bus sections, the two sections are briefly connected together via both disconnect switches without the possibility of being able to measure the individual current flows toward either of the sections. This upsets the current balance for the two bus zones and requires a special treatment as described later in 8.8.

The BF application is more complicated, too. When a given breaker fails, the BF trip signal is dynamically routed to those breakers that are connected to the same bus section at that time.

Even though the network elements connected to the same bus section as the failed breaker are cleared following the BF condition, they can be quickly and automatically restored to the other bus or the same bus after isolating the failed breaker.

As an alternative to dynamically assigning currents, two independent bus zones can be manually set up based on a set plan of service of the network elements, using, for instance, test switches. This simplifies the bus protection but decreases the flexibility of operation.

The double-bus single-breaker configuration is often further expanded toward a transfer bus capability. In order to use one of the buses as a transfer bus and the bus tie breaker as a substituting breaker, bypass switches are added to the network element breakers as shown in Figure 8. To maintain a given breaker, all network elements are routed to one bus, the network element of the said breaker is routed to the other bus, the bypass switch is closed, and the maintained breaker is isolated via its disconnects while the bus tie is closed and used to substitute the said breaker (Figure 9). Refer to 8.14 for more information on protection during breaker substitution.

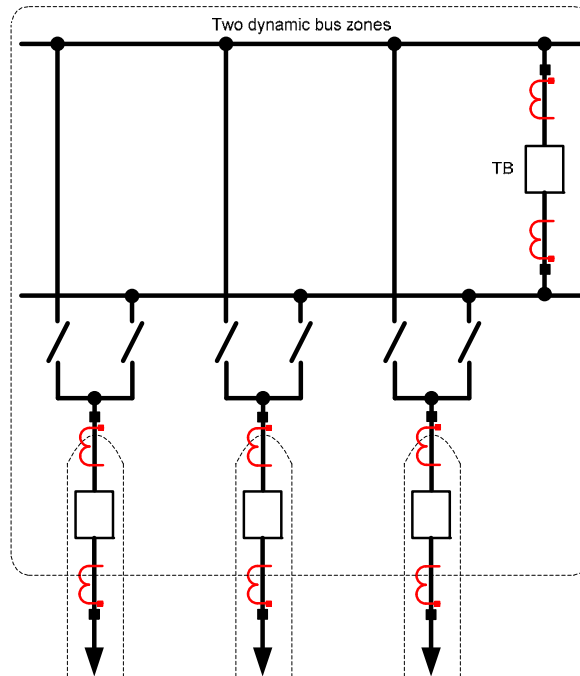


Figure 7—Double-bus single-breaker configuration

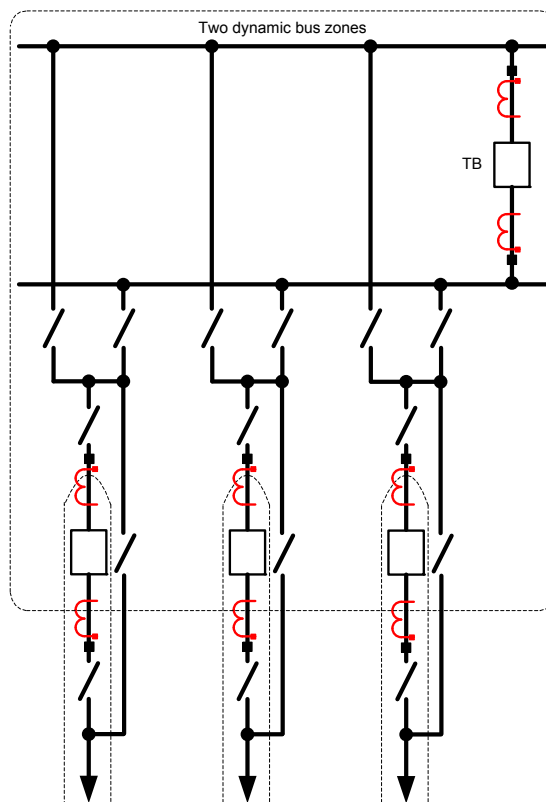


Figure 8—Double-bus single-breaker configuration with bypass switches

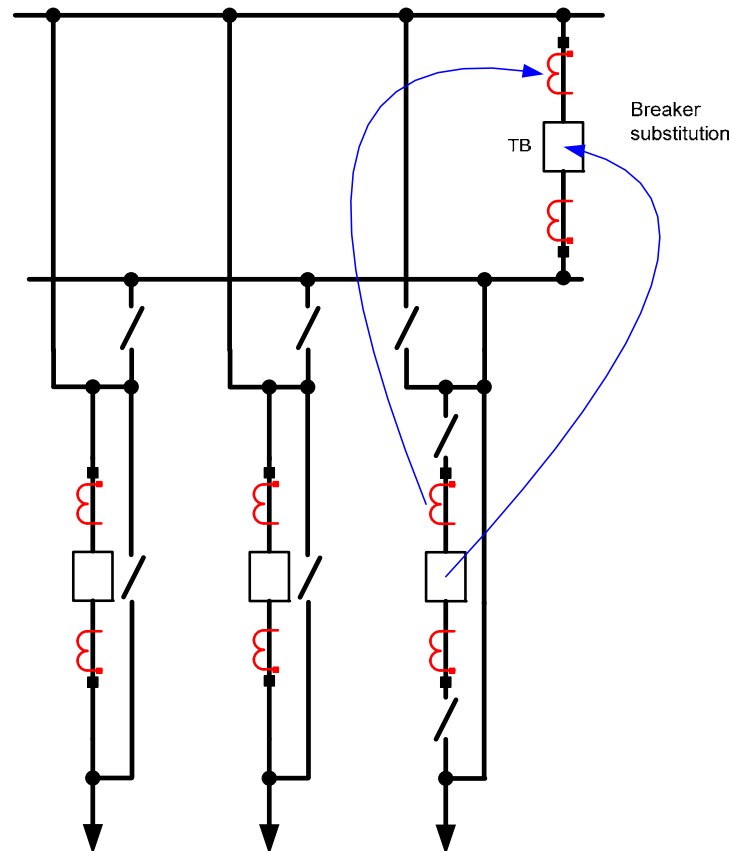


Figure 9—An example of a network element transferred to the bus tie breaker

4.5 Breaker-and-a-half

The breaker-and-a-half configuration is built on two bus sections connected via diameters of three breakers. Two network elements are tapped from each diameter as shown in Figure 10. In this way three breakers are required to connect two network elements, hence the designation *breaker-and-a-half*.

This configuration provides for very good flexibility and reliability, while allowing simple protection for both network elements and the bus sections. It is relatively economical, calling for 1.5 breakers per each network element.

Each breaker or bus section can be taken out of service for maintenance without interruption of service to any network elements. Breaker failure of any of the bus breakers calls for tripping the entire bus section, but no service is interrupted as each circuit is permanently supplied from both bus sections.

From the point of view of bus protection, protecting the breaker-and-a-half configuration is simple and equivalent to protecting two single bus sections.

From the viewpoint of the network element protection, dual-breaker relay application is required as explained earlier in conjunction with the double-bus double-breaker configuration.

In addition, the two breakers normally connecting a network element can be closed while the said network element is out of service or energized but isolated from the local bus via the disconnect switch. This is to

keep the diameter intact and supply the other network element on the diameter from both the bus sections. Such temporary configuration requires a special treatment known as *stub bus* protection, as described later in 8.16.

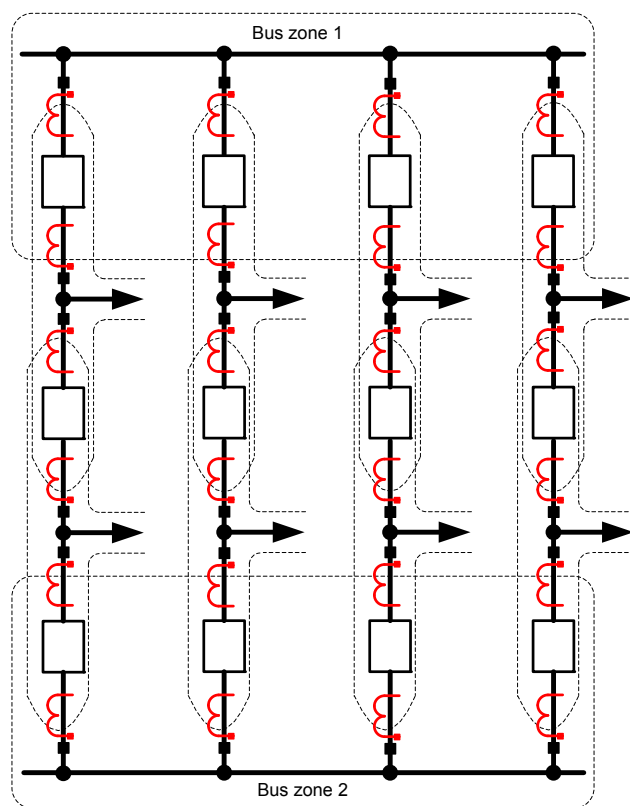


Figure 10—Breaker-and-a-half configuration

4.6 Ring bus

In the ring bus configuration a number of breakers—typically 4 to 6—are connected in a closed loop, hence the *ring bus* designation. Network elements are tapped between breakers as shown in Figure 11. In this way each network element is supplied via two breakers allowing maintenance of one of them without service interruption to any of the network elements. However, with a breaker out of service, the ring is broken and the benefit of reliability of supply is temporarily limited or lost. A danger of splitting an open ring bus into two sections upon a fault on any of the connected network elements arises and needs to be factored into the system planning and operation.

The configuration is economical, requiring basically one breaker per each circuit connected, but is limited in terms of the number of network elements that can be connected together and has a limited switching flexibility. Basically a ring bus is a connection point between a number of lines and transformers in a power system arrangement that requires these elements to be connected together under normal conditions.

The ring bus arrangement does not normally require bus protection. Overlapping zones of network element relays protect connections of breakers and disconnect switches.

In some cases, however, a dedicated bus zone may be needed to maintain sensitivity of protection for a connected network element in cases when the said network element does not feed much fault current, and

the load transfer through the bus is high. For example, if one of the network elements is a transformer with only load or weak source connected, it is beneficial to apply the transformer zone from the bushings of the transformer. This gives better sensitivity by not restraining the transformer relay from the large load current flowing through the two breakers. A dedicated bus protection zone is consequently needed between the two breakers and the transformer bushings to cover the transformer connections.

From the point of view of network element protection, the dual-breaker application is required as explained earlier with respect to the double-bus double-breaker configuration.

Similarly to the breaker-and-a-half arrangement, the two breakers of an out of service network element are typically closed in order to keep the ring intact. This calls for stub bus considerations as explained in 8.16.

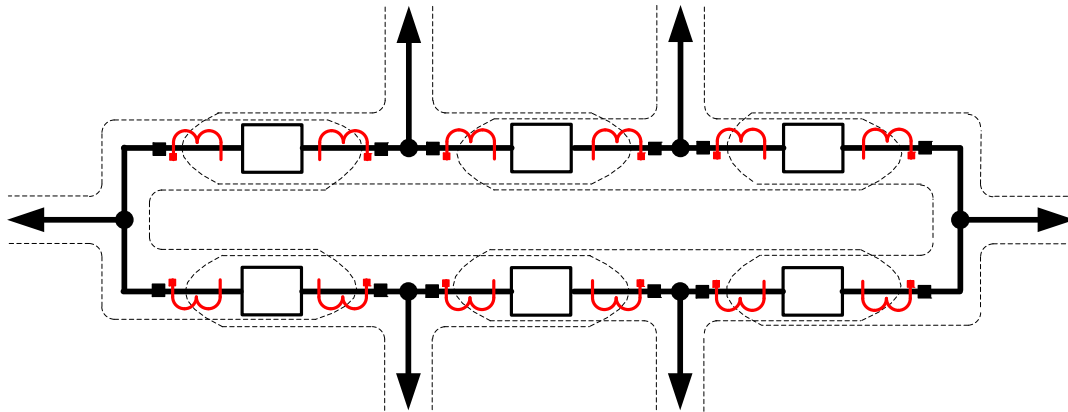


Figure 11 —A six-breaker ring bus configuration

4.7 Other bus arrangements

Practical bus configurations often exhibit irregularities due to expansions and modifications over the lifetime of a substation. For example, a diameter in a breaker-and-a-half configuration can be initially built to connect just one network element in a single-breaker arrangement to one of the buses, or in a dual breaker connection to both the buses. Only when the second network element is added, the said diameter may be fully expanded to contain all three breakers and form the regular breaker-and-a-half pattern.

In other cases bus configurations are continuations or re-combinations of the classical arrangements. Examples include triple or quadruple buses, double-bus single-breaker with a transfer bus, and so on.

Also, more structured and fully symmetrical bus configurations have been proposed, but not commonly used. These include breaker-and-a-third, crossed ring, ring tripod, ring bridge, 4 x 6 configuration, and others (see Anderson [B1]).

During the bus protection scheme engineering phase, it is typically sufficient to recognize the dominating characteristics of a given bus configuration, categorize it to one of the classical arrangements previously presented, and deal with exceptions using the general rules of bus protection.

5. Introduction to bus protection

A bus may be a critical element of a power system as it may be the point of convergence of many circuits i.e., transmission, generation, or load. Usually, due to the concentration of short-circuit sources, bus faults are of high current magnitudes. High-speed bus protection is often provided to limit the damaging effect on equipment or system stability or to maintain service to as much load as possible.

Inadequate bus protection can result in widespread system disturbances and equipment failures.

All this calls for dependability and availability of bus protection. On the other hand unnecessary operation of bus protection interrupts multiple network elements potentially causing system-wide problems or disrupting power supply to large number of loads. Therefore, security of bus protection is typically considered paramount.

The major types of bus protection systems are as follows:

- a) Differential
- b) Zone-interlocked schemes
- c) Time-coordinated relays that overlap the bus zone
- d) Fault bus
- e) Specialized sensors built into gas-insulated switchgear (not covered in this guide)

The major factors that influence the selection and design of the bus protection system are as follows:

- 1) Bus arrangement and operational flexibility
 - Fixed bus arrangements
 - Switchable (reconfigurable) bus arrangements
- 2) Availability and characteristics of CTs
- 3) For reconfigurable buses, availability of auxiliary contacts of disconnect switches
- 4) Performance requirements of the application
 - Security
 - Selectivity
 - Speed
 - Sensitivity
- 5) Cost and complexity

This clause of the guide briefly introduces principles of bus protection, introduces major types of bus protection schemes, and reviews factors influencing selection and design of bus protection schemes.

5.1 Zones of bus protection

In terms of its ability to detect bus faults, the bus protection zone is defined by location of CTs surrounding the bus. In terms of its ability to clear the fault once detected, the bus protection zone is defined by location of breakers surrounding the bus.

Ideally, bushing CTs are located on both sides of a breaker, and the breaker is overlapped by the bus and network element protective relaying zones as shown in Figure 12. As a result, no blind spots exist in the system, and the measuring boundary of the bus protection zone is slightly larger than the tripping boundary of the bus zone.

Bus protection schemes reviewed and categorized later in this clause perform a task of detecting an internal bus fault within the measuring boundary of the zone of protection, with the intent to issue a trip command to the breakers located on the tripping boundary of the zone.

For maximum selectivity, a dedicated zone of protection covers each bus section with its own measuring and tripping boundaries.

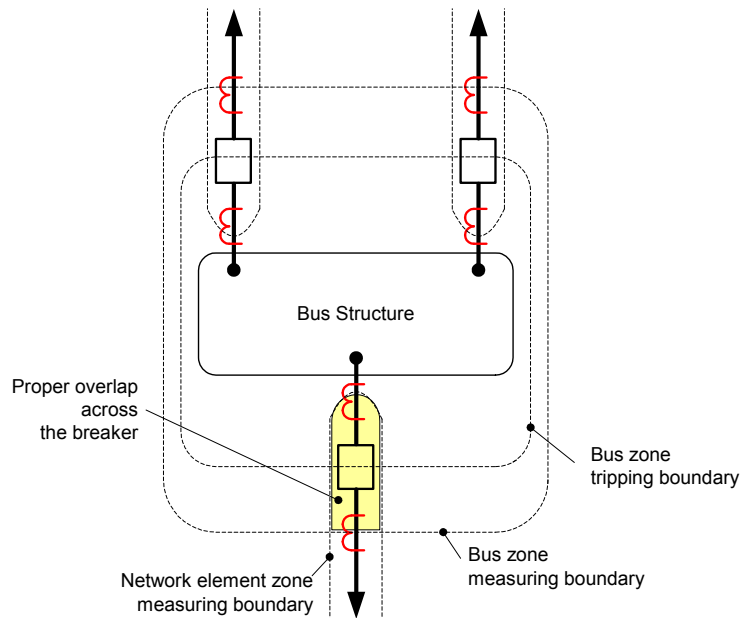


Figure 12—Proper measuring and tripping boundaries of bus and network element zones of protection

Several exceptions can be considered as a part of the basic principles of bus protection.

As a rule live-tank breakers are accompanied with freestanding CTs. Each phase has a separate freestanding device containing multiple CT cores. To realize the economy of live-tank breakers, these CTs are typically located on one side of the breaker only. Hence, the breaker will be within only one of the overlapping protection zones as shown in Figure 13 and Figure 14.

Figure 13 is the case of a *line-side CT* where the freestanding CT is located between the breaker and the connected network element. The term *line* refers here to any network element associated with the bus. In this case the section of the primary conductors, between the breaker and the CT, calls for a special treatment. This is a blind spot for the protection of the network element, and it is an over-tripping spot for the bus protection, should the breaker be opened.

Figure 14 is the case of the *bus-side CT* where the freestanding CT is located between the breaker and the bus. In this situation the primary conductors between the breaker and the CT are in the blind spot for the bus protection, and are an over-tripping spot for the network element protection should the breaker be opened.

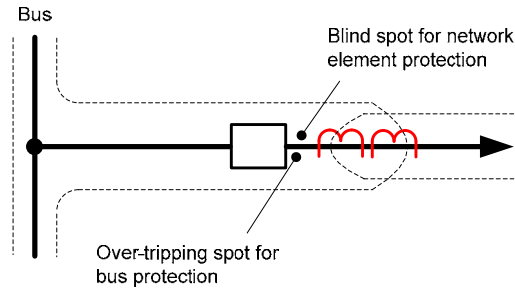


Figure 13—The case of a line-side current transformer

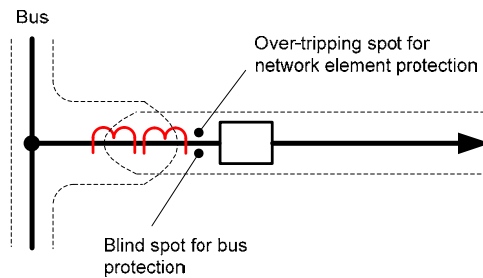


Figure 14—The case of a bus-side current transformer

The preceding situation applies not only to live-tank breakers but may take place in other applications due to size or economical limitations preventing installation of CTs on both sides of a breaker.

In general there is no perfect location of a single CT with respect to its breaker and the bus. The chosen location depends on the availability of means of solving the problem created by the lack of overlap of the two zones across the breaker. These solutions are discussed in detail in 8.12.

Stub bus protection is another consideration related to measuring and tripping boundaries of the protection zones. As shown in Figure 15 a dual-breaker connection to a network element can be kept closed for maintaining integrity of the bus (ring bus and breaker-and-a-half configurations) while the network element is disconnected from its breakers and CTs via a disconnect switch. Depending on the type of protection applied to the network element this situation may cause security and/or dependability problems for the network element, and dependability problems for the area between the two closed breakers and the opened disconnect. Stub bus considerations are discussed in detail in 8.16.

Reconfigurable buses such as double-bus single-breaker require both the measuring and tripping boundaries of bus zones to adjust dynamically to follow the actual bus configuration. This is illustrated in Figure 16 where the shown breaker and CT can be connected to two or more buses via disconnect switches. This application calls for dynamic association of currents to the measuring zones, and breakers to the tripping zones and is known as *dynamic bus replica* (see 8.8). This application includes not only the detection and isolation of bus faults, but also tripping under BF conditions. For this reason in applications calling for the dynamic bus replica the bus protection and BF protection functionalities are often integrated.

There are more applications that benefit from the ability to dynamically include and exclude currents and breakers from the bus protection zones, as described in 8.8. Annex B provides an example of application of the dynamic bus replica.

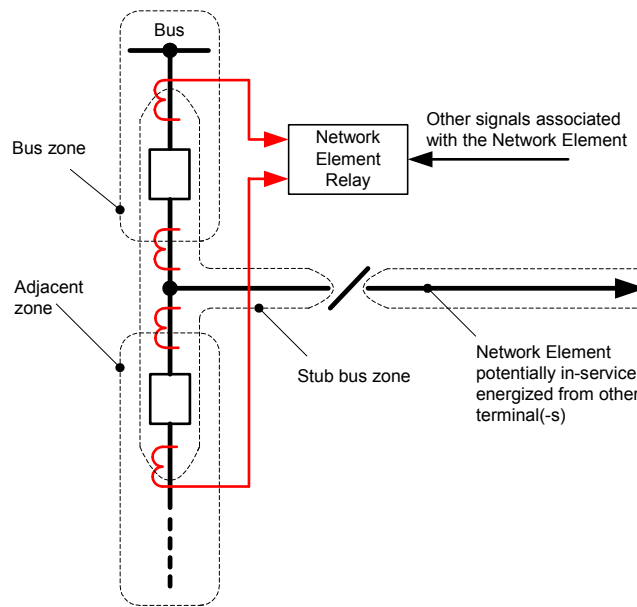


Figure 15—Stub bus configuration

Finally, in some applications a CT and/or a breaker are not installed on some of the network elements connected to the bus, typically radial loads or shunt capacitor banks. In such cases the said network element becomes a part of the bus as there is no provision to pinpoint the exact fault location between the bus and the network element, and there is no means to isolate the network element from the bus. Such applications are engineered as partial bus protection zones as explained in detail in 8.1.

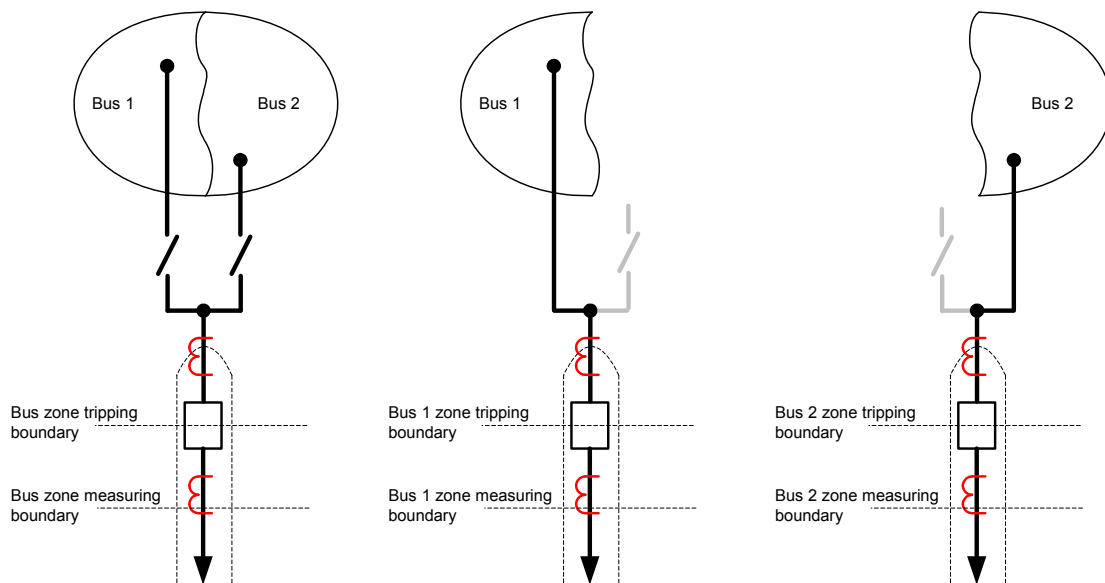


Figure 16—Bus zone boundaries for a reconfigurable bus

5.2 Types of bus protection

It is convenient to describe the general types of bus protection schemes and their characteristics before describing their suitability for a given application.

5.2.1 Differential

Any relay that has information on the sum of all currents entering and exiting the zone of protection and operates on the difference in these currents falls under the category of differential relaying. There are five general categories of differential relays used in bus applications, as follows:

- Differentially connected overcurrent (instantaneous or time delayed)
- Percentage-restrained differential (or differential with other means of dealing with CT saturation)
- High-impedance differential
- Partial differential overcurrent
- Fault bus

Differential protection is often applied on bus protection for its high selectivity. All currents into and out of a zone of protection are measured. The zone of protection is determined by the location of the CTs that define the differential zone. With high selectivity, a differential relay does not need to have any intentional time delay to coordinate with relays in adjacent zones. Thus, differential protection can provide high speed of operation. As mentioned previously, there are a number of different types of differential relays. Each has different levels of performance with regard to ultimate speed, selectivity, sensitivity, and security.

The other attribute of differential relays is their relatively high sensitivity. The relay operates on the difference current instead of the through current in the system. Thus, it can have much greater sensitivity than an overcurrent or distance relay that is typically set above the load flow through the protected zone. However, for a bus protection application, high sensitivity is generally not particularly critical. The exception to this is on buses where the minimum fault current levels are very low, such as on a high-impedance grounded system.

5.2.1.1 Differentially connected overcurrent (instantaneous or time delayed)

Differentially connected overcurrent relays respond to the magnitude of the difference current. Their inherent limitation is that they can operate on false differential current caused by CT saturation so they are relatively insecure compared to most other differential relaying principles. There are several means to enhance their security, as follows:

- Set the pickup above the worst case anticipated false differential current.
- Use time delay, typically inverse timing, that will trip fast for high differential current but slow enough to ride through asymmetrical saturation until the CT recovers.
- Add a small stabilizing resistance to the differential leg of the CT circuit to reduce the amount of false differential current that flows to the relay.

The first two remedies require analysis that is beyond the capability of simple engineering tools. Often, settings fine-tuned over years of field experience and based on heuristic rules developed by protection engineering departments are applied. To avoid such heuristic approaches, more advanced, easier to set differential relays can be used.

See 7.1.1 for detailed discussion of this scheme.

5.2.1.2 Percentage-restrained differential

The percentage-restrained characteristic operates on the ratio of the following:

- Operate current (differential current)
- Restraint current (a measure of the through current in the bus zone)

The ratio of operate to restraint current is referred to as the *slope*, which is often expressed in percentage, hence the designation. There are multiple ways of defining the slope characteristic (variable percentage slope versus fixed percentage slope). There are multiple ways of defining the restraint current also. When the operate current divided by the restraint current exceeds the slope characteristic, the relay operates.

Modern microprocessor-based relays apply more sophisticated means to cope with spurious differential currents caused by CT saturation, in addition to using percentage restraint only.

See 7.1.3 for detailed discussion of this scheme.

5.2.1.3 High-impedance differential

High-impedance differential relays place a very high burden (around 1000 Ω to 2000 Ω) in the differential leg of the CT circuit. The relay typically responds to the voltage measured across the summing point in the CT circuit. If an internal fault on the bus occurs, all CTs try to force the differential current through the high impedance. All of the CTs will typically saturate and a much distorted high voltage will appear across the CT circuit summing point. These schemes include means of limiting the voltage in the circuit to prevent CT, cable, and relay insulation breakdown.

For an external fault, the differential current sums to zero and no current flows in the high-impedance branch of the circuit. If a CT saturates during an external fault, the impedance of the circuit branch of the saturated CT is much less than the impedance of the circuit branch to the differential relay. The voltage elements of the relay are set above the highest voltage that can be seen across the summing point of the CT circuit for an external fault. This is obtained by assuming that a CT saturates completely. This protection system provides both high security for external faults and high sensitivity for internal faults. The high sensitivity is provided because very little difference current is required to create a voltage drop across the high impedance to allow a trip. This scheme is especially suitable to high-impedance grounded systems for this reason.

See 7.1.2 for detailed discussion of this scheme.

5.2.1.4 Partial differential overcurrent

This scheme is closely related to the differentially connected overcurrent scheme except that there are some network elements connected to the bus that are not monitored, typically because of lack of CTs. A typical example would be a bus with radial loads that has multiple sources such as a main and a tie. The source circuits would be included in the differential circuit; but, the non-source network element breakers (e.g., feeder breakers) may not because CTs are not available or they are not adequately rated for differential application. Partial differential is sometimes used as a combined backup for the main bus and feeder protections. A bus with a fuse-protected bus-connected shunt capacitor bank is another typical example. This scheme has somewhat reduced sensitivity than a true differential scheme because its minimum pickup is set above the maximum current in the unmonitored circuit(s). This scheme can be set to operate instantaneously if it is deemed acceptable to trip the bus for faults in the unmonitored network elements. Otherwise, time coordination is required to maintain full selectivity.

See 8.1 for detailed discussion of this application.

5.2.2 Fault bus

A fault bus scheme uses an instantaneous overcurrent element that responds to the fault current flowing to ground from the bus structure. This scheme is typically limited to distribution level voltages and metal-clad switchgear where it is possible to insulate the entire bus structure from ground except for one grounding jumper. The grounding jumper is passed through a CT to measure any ground fault current. The scheme responds to ground faults and will not detect phase to phase faults.

Technically this scheme is a differential scheme as it effectively responds to the sum of all the currents surrounding the bus, even though the said differential current is measured directly owing to the controlled way of grounding the bus structure. Being differential, the fault bus scheme allows for high speed and good sensitivity for ground faults.

See 7.3 for detailed discussion of this scheme.

5.2.3 Zone-interlocked schemes

Any scheme that relies upon relays on the network elements to signal the location of the power system fault falls under the category of a zone-interlocked scheme. There are two general categories of zone-interlocked schemes used in bus applications, as follows:

- Simple blocking
- Directional blocking

These schemes are simple to apply in configurations where the network element relaying can determine that the fault is on the protected circuit and not on the bus. With directional relays it is possible to use this bus protection method with multiple sources, but the application becomes more complex.

These schemes are also particularly suitable to applications where the bus can be sectionalized by disconnect switches instead of circuit breakers. It takes simple logic to reconfigure the zones based upon which sources and network elements are on which bus sections to maintain selectivity.

5.2.3.1 Zone-interlocked simple blocking schemes

Simple blocking schemes are suitable for radial applications. In a blocking scheme, the relays on the network elements are connected to a relay measuring the source circuit(s) such that they can block the source relay from tripping if they detect a fault on their network elements. The tripping elements on the source relay are delayed only long enough so that the blocking logic will reliably assert if the fault is external to the bus. Delay is typically on the order of one to two cycles.

5.2.3.2 Zone-interlocked directional blocking schemes

Directional blocking schemes are suitable for networked applications where multiple network elements are sources to the bus. Directional blocking schemes typically rely upon directional elements in each network element to assert “fault towards bus” or “fault away from bus” logic. The logic is set up such that if any one relay sees a fault towards the bus and no other relay sees a fault away from the bus, the bus is tripped. The logic includes a small coordination delay so that the “fault away from bus” blocking elements have enough time to assert. Delay is typically on the order of one half to one cycle.

See 7.2 for detailed discussion of these schemes.

5.2.4 Time-coordinated relays that overlap the bus zone

When there is a lack of a dedicated bus protection scheme, faults in the bus zone are cleared by time-coordinated relays that overlap the bus zone. Examples include relying upon remote zone 2 step distance relays to time out and trip for a bus fault beyond the protected line; or, in radial applications, simply a time-coordinated overcurrent element on the source breaker to the bus.

Selectivity can be enhanced (the remote line terminals are not tripped) if either a local forward element with offset to include the origin or a local reverse element starts a timer that is coordinated with the remote overreaching distance zone timers to trip each network element of the bus.

This scheme has poor speed performance compared to most of the dedicated bus protection schemes.

In a non-redundant bus protection scheme, these techniques are relied upon for backup protection of the bus.

5.3 Considerations for bus scheme selection

The factors to consider in selecting a bus protection scheme for a particular application include the following:

- Bus arrangement
- Availability and location of CTs
- Characteristics of available CTs
- Availability and location of voltage transformers (VTs)
- Performance requirements
- Cost and complexity

These factors are discussed individually below. Table 1 contains recommendations on the application of the various bus protection schemes based on these factors.

5.3.1 Bus configurations

The station arrangement has a major influence on how the bus protection system is designed. Detailed description of all of the common station arrangements is given in Clause 4. In the context of selecting the type of bus protection the most important distinction is between fixed and switchable bus arrangements.

In fixed bus arrangements, the configuration of the bus zones and circuit breakers and their associated network elements connected to them are fixed. There is no need to reconfigure the zones of protection and the CTs that are associated with each. However, under special conditions such as a breaker with a single CT, it may be beneficial to make some of the associations dynamic even for fixed bus configurations, as explained in 8.12.

In switchable bus arrangements, circuit breakers and their associated network elements can be connected to more than one bus by disconnect switches. Thus, some means of reconfiguring the bus protection is required.

5.3.2 Availability and location of current transformers

The availability of CTs to define the bus zones is an important consideration. If CTs are not available on every network element, full differential protection is not possible. In this case, partial differential overcurrent or time-coordinated relaying may be used. If CTs are available on every network element around the bus, differential relays may be applied. Some differential schemes such as high-impedance differential require a dedicated set of CTs to make up the differential circuit. If the CT circuits are shared with other protection systems, a low impedance differential scheme such as differentially connected overcurrent or percentage-restrained differential relays may be selected.

With electromechanical relays, the differential current is summed by physical connection of all of the CTs in the differential circuit. It is desirable to not place additional electromechanical relays in the circuit in order to limit the burden. Most microprocessor-based relays have isolated CT inputs and negligible burden such that it is possible to use a CT circuit in a low impedance differential scheme for other relaying schemes. In these relays, the differential current is obtained mathematically internal to the relay. This makes it possible to improve the zones of protection in an existing substation with available CTs or reduce the number of CTs required in new installations.

5.3.3 Characteristics of available current transformers

In differential relay applications where the differential current is made up by physical summation of the CT circuits, matching the ratio of the CTs can also present a problem. If CTs of suitable common ratio are not available, a bus protection system that can tolerate mismatched ratios would be selected. Modern microprocessor-based bus differential relays accept high mismatch ratios.

The ratings of the CTs can also influence the choice of the bus protection system. CTs with too low an accuracy rating or too low a ratio versus the available fault current can make certain types of bus protection systems not suitable. For example, if there is not adequate margin between the secure voltage setting of a high-impedance differential relay and the lowest burden voltage rating in the CT circuit, a high-impedance relay might not be able to trip dependably due to the CT clamping the voltage in the circuit too low. If any of the CTs are not adequate to limit saturation to a reasonable level, a simple percentage-restrained differential relay may not have adequate security. An advanced differential relay with a CT saturation detector may be required.

5.3.4 Availability of voltage transformers

Zone-interlocked directional blocking schemes typically will require VTs for polarizing the directional elements.

Voltage elements are also sometimes applied to enhance security in bus differential applications where the zones of protection are switched (switchable bus arrangements). Differential current without a corresponding change in the voltage indicates a dynamic bus replica error instead of a short circuit on the bus.

5.3.5 Performance requirements

Bus protection systems can be evaluated based upon performance criteria. These include the following:

- Selectivity
- Speed

- Sensitivity
- Security

5.3.5.1 Selectivity

Bus protection systems generally require high levels of selectivity. The impedance of the protected circuit, fault current levels, and time delay can achieve selectivity in other applications. These factors do not apply to bus applications, and therefore, an inherent selectivity of the protection system is required by appropriate shaping of the bus zone measuring and tripping boundaries. That is why some form of differential protection is often chosen. Zone-interlocked schemes achieve selectivity by logic.

5.3.5.2 Speed

Various schemes can have different levels of performance. Zone-interlocked schemes include a delay to coordinate with the receipt of blocking signals. Traditional percentage-restrained relays tend to be somewhat slower than advanced percentage-restrained relays with high-speed algorithms. High-impedance differential relays tend to be very fast since the voltage reaches tripping levels in fractions of a cycle, and no intentional delay is needed for security or selectivity.

The ultimate speed requirements of the bus protection system are determined by system stability, power quality, and equipment through-fault withstand.

5.3.5.3 Sensitivity

Normally, sensitivity is not a very critical requirement of bus protection systems. Typically, high-impedance faults are not likely due to the fact that the bus work is surrounded by solidly grounded structures. Arc resistance can reduce the fault current. Insulators on open-air buses are subject to power flashover and arcing when exposed to conditions such as a combination of salt contamination and fog, moisture, or ice (see Bartnikas [B3]).

Impedance grounding will decrease ground fault levels. In this case, the difference between phase fault levels and ground fault levels can require a bus protection system that includes higher sensitivity for ground faults.

Differential relays, due to the fact that they operate on the difference current and not the through current in the circuit tend to have higher sensitivity than other protection systems such as distance or overcurrent based systems. High-impedance differential relays have much higher sensitivity than percentage-restrained differential relays. Zone-interlocked systems can achieve the required sensitivity if all of the relays that protect the network elements have adequate sensitivities.

5.3.5.4 Security

Security is paramount for bus protection. Tripping of a bus for an external fault can have a significant effect on the power system in loss of loads and in simultaneously taking out multiple transmission paths. Some bus protection schemes have inherently greater security than others. Simple differential overcurrent and partial differential schemes have low inherent security. Zone-interlocked systems have better security. Percentage-restrained differential systems have higher security. The best security performance can be achieved with advanced percentage-restrained differential relays with CT saturation detector functions and other features to enhance security, and with high-impedance differential systems.

5.3.6 Cost and complexity

Cost is often a consideration in determining the appropriate protection system as long as performance criteria are met. The cost of the protection system itself is only one of the costs to be evaluated; the cost of the protection system includes:

- Cost of protective relays and cabling that make up the system.
- Cost of instrument transformers required to implement the protection system.
- Cost of engineering studies to verify adequate performance of the protection system.
- Cost of testing and validation of the protection system (see IEEE Std C37.233™ -2009 [B18]).

Complexity can introduce hidden costs. For example, even though zone-interlocked systems make use of the relays on each of the network elements and therefore do not require dedicated bus protection system equipment, they can be much more complex than a dedicated differential system to design, set, and commission.

Simple differential overcurrent relays may make use of a low cost overcurrent relay, but the engineering studies required to verify a high level of security can be quite expensive. This scheme is only economical if the end user does not require a high level of security and/or speed.

In many cases a trade-off is possible between the amount of engineering effort and the cost of equipment required.

5.3.7 Bus scheme selection matrix

Table 1 provides a matrix that can be used to help evaluate the applicability of various bus protection systems based upon several criteria. ⁶ The letters in the evaluation matrix indicate the following:

R = Recommended

N = Not recommended

H = Relatively high

M = Relatively medium

L = Relatively low

⁶ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

Table 1—Bus protection selection table

	Differentially connected overcurrent	Percentage-restrained differential	Advanced percentage-restrained differential	High-impedance differential	Partial differential overcurrent	Zone-interlocked simple blocking	Zone-interlocked directional blocking	Time-coordinated relays that overlap the bus zone
Breaker/bus arrangements								
Fixed bus arrangements		R	R	R				
Switchable bus arrangements			R (see NOTE 1)	N (see NOTE 1)				
Bus sectionalized with switches			R			R	R	
Buses with low minimum short-circuit levels				R		R	R	
Available CTs								
Dedicated CTs available		R	R	R				
Share bus protection CTs with other protection		R	R	N		R	R	
Unmonitored network elements		N	N	N	R	R	R	R
CTs with unmatched ratios	N	R	R	N (see NOTE 2)		R	R	
CTs with low accuracy class	N		R (see NOTE 3)	R (see NOTE 4)				
Performance								
Selectivity	H	H	H	H	L	H	H	L
Speed	H (see NOTE 5)	M	H	H	L (see NOTE 6)	M	M	L
Sensitivity	H (see NOTE 5)	M	M	H	L	M	M	M
Security	L	M	H	H	L	M	M	H (see NOTE 7)
NOTE 1—It is recommended to avoid switching CT circuits. Microprocessor-based differential relays can assign (switch) CT circuits between zones of bus protection in software. NOTE 2—There are techniques for dealing with mismatched CTs in a high-impedance bus differential application, but other relay systems can more easily deal with this problem. NOTE 3—Assuming that the advanced percentage-restrained differential relay has functionality to put it in a high security mode if CT saturation is detected or the fault has been determined to be external. NOTE 4—Assuming that the burden voltage rating is great enough to satisfy both security and dependability criteria. NOTE 5—If a stabilizing burden is installed in the differential leg of the CT circuit. Otherwise, speed and sensitivity are poor. NOTE 6—Speed is low unless over-tripping for faults on the unmonitored network elements is acceptable. If it is, speed can be adequate. NOTE 7—Assuming that the time coordination is adequate.								

Cost and complexity are not included in the matrix because they depend upon many factors that cannot be simplified for this table. These recommendations are based on typical scenarios, and may not be appropriate for all cases.

Selection of a proper bus protection scheme requires in-depth knowledge of the many involved factors. This clause provides general guidelines only. Refer to specific clause of this guide for more detailed explanation of performance, limitations, characteristics and trade-offs of the various methods.

6. Relay input sources

6.1 Current transformers

CT performance and capability are critical to the successful operation (dependability) of bus protection for in-zone faults and even more critical for successful non-operation (security) for external faults. This clause reviews specific CT topics that are essential for the correct application to bus protection. Detailed CT requirements for different types of bus protection methods are given in their specific clauses.

For actual CT selection, there is a wealth of literature on CT construction, principles of operation, and CT transient behavior. See for instance IEEE Std C37.110.

6.1.1 Current transformer types used in bus protection

The following lists the types of CTs used in bus protection:

- Iron-core class C or X CTs (the 2008 revision of IEEE Std C57.13 replaced the K accuracy class with the X accuracy class)—The most common class for primary current measurement. The class rating system is discussed later in this clause. These are constructed on an iron core with no gaps in the circumferential direction and with the secondary winding distributed around the core. They have negligible excitation current until saturation voltages are reached, but with remanence of up to 90%.
- Gapped-core CTs—These are also class C or X (), but vary from the previous in that one or more gaps of non-ferrous material are introduced in the circumferential direction. They have significant excitation current even below saturation, but with remanence limited to 10%.
- Auxiliary CTs—Used in the CT secondary circuits of differentially connected schemes where required to compensate for mismatch in the ratios of the primary CTs. Also used to limit the burden effects of metering devices on protection performance by saturating for fault level current. These may be class C or X (K), but are more often class T.
- Linear couplers—Mutual inductors with non-ferrous cores, used for differential bus protection in voltage-differential (series connected) mode. Since the linear coupler core is non-ferrous there is no saturation and the output is a voltage.
- Non-conventional CTs (transducers)—Often referred to as *electronic current transformers* (ECTs), these belong to a new generation of current sensors that includes Rogowski coils, low-power iron-cored current sensors, and optical current sensors. Relays using these need to be designed to accept the signals generated by the particular ECT involved.

6.1.2 Current transformer relaying accuracy classes

The IEEE (ANSI) CT relaying accuracy class is written as a letter designation and a secondary terminal voltage rating, for instance C400. This designation describes the steady-state performance (see IEEE Std C57.13).