COMMISSIONING AND TESTING COMPLEX BUSBAR PROTECTION SCHEMES - EXPERIENCE AT PACIFIC GAS & ELECTRIC

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1. Introduction

As "junction points" at all voltage levels, carrying energy in electric power schemes, power substation buses are critical to scheme topology. Exposure to high-fault currents imposes stringent performance requirements on both bus protection relays and current transformers. Saturation of current transformers (CTs) caused by external problems may jeopardize the security of bus protection due to unbalanced currents in the differential relay.

Improper operation of a bus relay, in turn, considerably changes scheme topology and significantly impacts both power delivery, in the case of a distribution bus, and scheme stability in the case of a transmission-level bus.

Historically, Pacific Gas and Electric Company (PG&E) has standardized on the double-bus single-breaker arrangement for major transmission buses (Figure 1).

The standard protection for these buses has been a high impedance bus differential relay. The single breaker double bus configuration, formerly used, required complex switching of the bus differential CT, dc tripping circuits and breaker failure tripping circuits whenever the bus configuration was changed by operating the bus isolator switches. Operations personnel were often required to execute more than 100 switching steps to reconfigure the bus in order to take one breaker out of service by bypassing and clearing it while maintaining protection of the circuit using a substitute breaker.

Low-impedance microprocessor-based bus protection schemes have provided a better solution to protecting the double-bus single-breaker bus configuration. Such schemes monitor all currents as well as the positions of breakers and isolators, and dynamically adjust their zones of protection for

Fig 1.
115 kV single breaker double bus and control building.

Fig 2.
60 kv bus with outdoor relay cabinet and indoor control building

optimum selectivity while the bus is being switched. These schemes do not require operator intervention, which saves time and reduces the risk of an incorrect operation. The schemes can also be installed in outdoor cabinets close to the protected bus, reducing the length of CT wiring to the differential relays (Figure 2).

Other reasons for the increasing penetration of low-impedance microprocessor-based relays are their advanced monitoring functions, integrated breaker failure protection, and cost. This penetration became particularly noticeable after several vendors released affordable phase-segregated low-impedance bus relays around 2002 [1].

Lastly, and most importantly, the installation a low-impedance differential makes it easier to accommodate added generation or expansion of existing buses because it is not necessary to change existing CTs or add slip-on CTs as is sometimes required for high-impedance bus differentials.

The high-impedance bus differential requires that all CTs have the same ratio, preferably no tapped CT windings, and similar excitation characteristics. Traditionally, robust high-impedance schemes may fail to operate correctly if all the CTs are not properly matched. Modern low-impedance solutions show very high immunity to extreme cases of CT saturation; in many such cases, performance is better than that of the high-impedance schemes [2]. The low-impedance microprocessor-based relay is a complex piece of protection equipment to commission. Quite often the scheme consists of many ac current inputs, ac voltage inputs, trip outputs, and several - perhaps hundreds - of status inputs.

This paper reviews some of the basics of bus protection, discusses some unique logic requirements for handling switching and bypassing of breakers on a double-bus single breaker configuration, and focuses on some of the practical aspects of commissioning complex bus schemes.

2. Cost-Efficient Bus Protection Schemes

While monitoring bus configuration is unimportant for many bus arrangements (Figures 3 and 4), for other configurations monitoring bus topology and following it in terms of measuring and tripping zone boundaries, is essential (Figure 5).

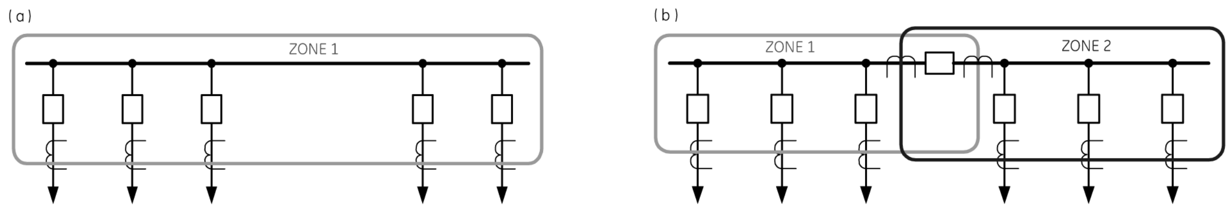
Reconfigurable buses, such as is shown in Figure 5, are best protected by low-impedance microprocessor-based bus differential schemes. Such schemes recently became quite affordable and relatively easy to install, with the introduction of a phase-segregated version such as solution [3-4].

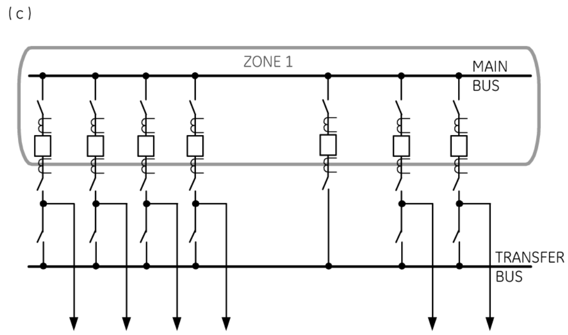
From the perspective of the most important area of protection, the bus differential function (algorithm) is naturally phase-segregated, which means that no information is required regarding currents in phases B and C in order to fully protect phase A. The results are as follows [2-4]:

- Completely independent microprocessor-based devices can process the ac signals that belong to phases A, B and C. No data transfer is required between the individual devices of the bus protection scheme.

- Sampling synchronization is not required between the separate microprocessor-based relays that process signals from individual phases.

These facilitate phase-segregated busbar protection. In Figure 6, three separate relays (Intelligent Electronic Devices (IEDs)





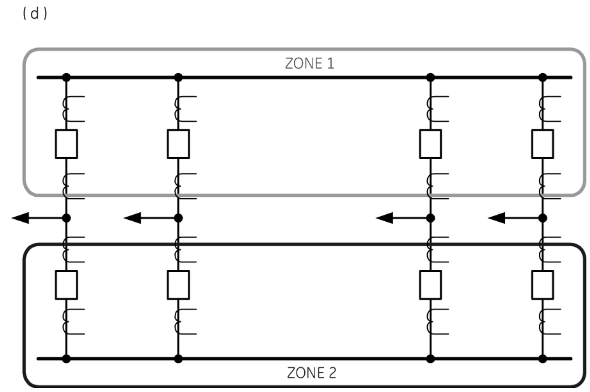


Fig 3.
Bus arrangements: single-bus single breaker (a,b), single-bus single-breaker with a transfer bus (c), double-bus double-breaker (d).

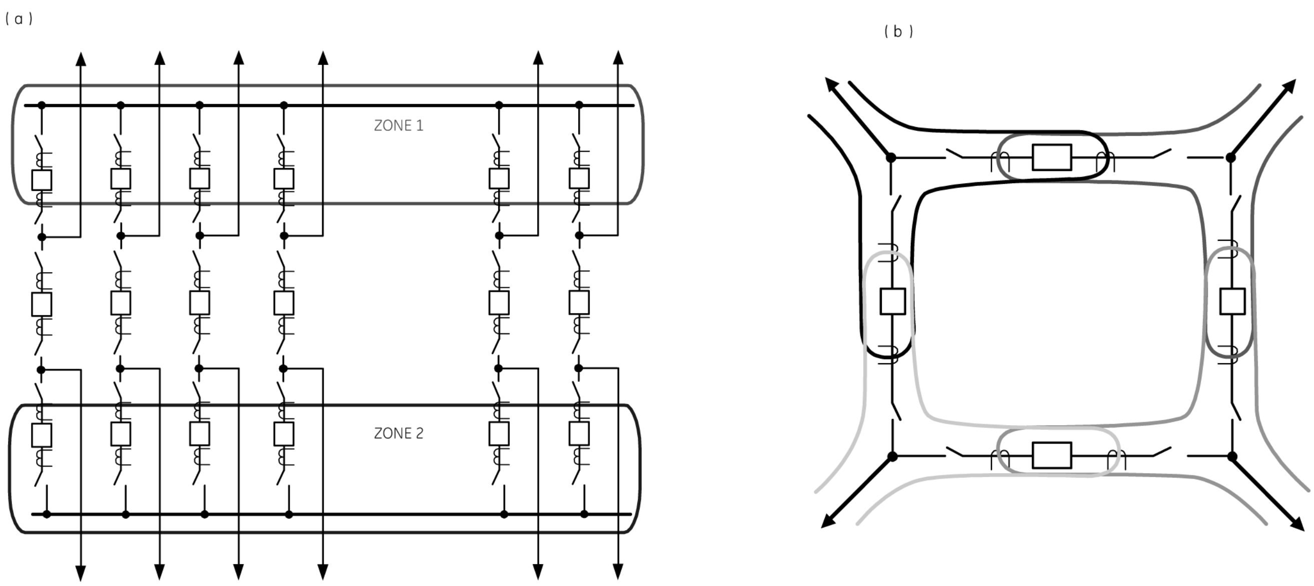


Fig 4.
Bus arrangements: breaker-and-a-half (a) and ring-bus (b).

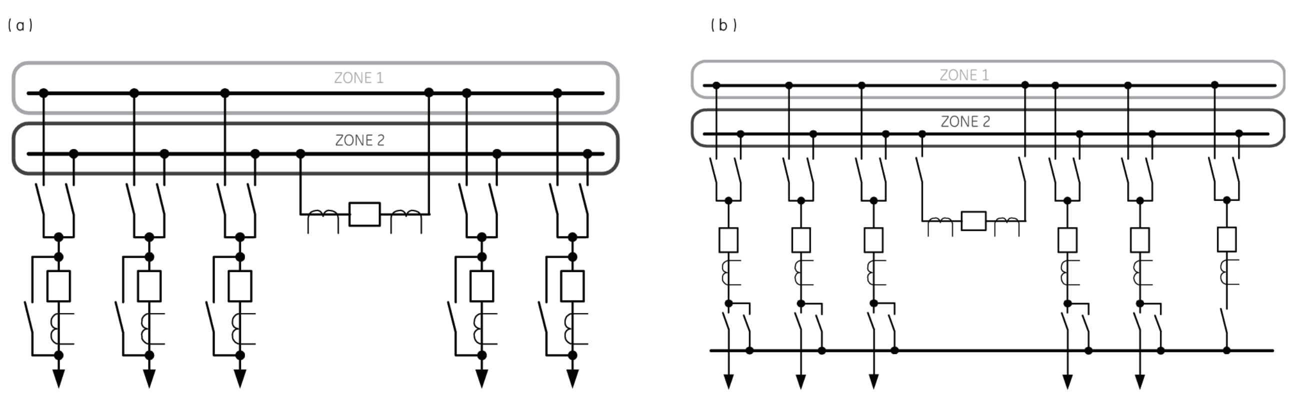


Fig 5.
Bus arrangements: double-bus single-breaker without (a) and with (b) a transfer bus.

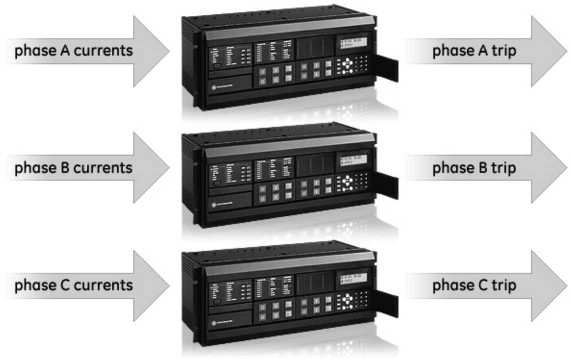


Fig 6.
Idea behind phase-segregated bus protection schemes.

[1]) are used to provide protection for a three-phase busbar. Each phase of each device is fed with its own ac currents and voltages, the signals are processed, and the trip/no-trip decision is made. At least one device operates for any type of fault. For phase-to-phase faults, two relays operate.

Traditional low-impedance bus differential protection schemes monitor all bus currents, derive differential and restraint signals, and apply these signals to a pre-configured operating characteristic for the tripping/restraining action.

Modern relays [1,2] sample their input signals relatively fast 64 samples per cycle, or faster – and are therefore capable of incorporating sophisticated and robust means of dealing with CT saturation while maintaining excellent sensitivity and speed of operation.

3. Switching Procedures in Typical Double-Bus Configurations

Double-busbar configurations in this case study, have 9 or 10 circuits on average, connected via isolator switches to either bus, have a bus coupler connecting the two buses, and use sectionalizing breakers to divide bus sections (Figure 5a). In addition, each feeder circuit breaker is equipped with a by-pass switch. This switch facilitates breaker substitution where the coupler is temporarily used to protect any of the feeder or transformer bank circuits when the original breaker is taken out of service for maintenance. During the breaker substitution, one bus becomes a part of the transmission circuit, with all the other circuits routed to the other bus.

Low-impedance differential protection applied in this case [1] provides continuous monitoring of all isolator switches, and dynamically includes or excludes currents into or from the applied differential zones. Allocation of trip commands to individual breakers follows this dynamic bus image. The same situation applies to trip commands from the breaker fail function where the secondary breakers are selected dynamically for the failed breakers based on the topology of the busbar at the moment. The isolators are switched either manually or automatically. When a circuit needs to be transferred from one bus to the other, the isolator switch connecting the circuit to the target bus is closed, after which the other isolator, connecting with the original bus, is opened, and the transfer is complete.

Isolator positions are indicated by LEDs on the relay faceplate, allowing the operator to validate that the bus differential relay is accurately reading the bus configuration before and after switching.

For a short time, when both isolators are closed during switching, the two buses are connected together via the isolator switches of the transferred circuit. In the case of a fault occurring at this time, the faulted bus cannot be separated from the other bus (no breaker; two isolators connected in series). In addition, the relay cannot identify the faulty bus (Bus #1 or Bus #2) as the CT associated with the transferred circuit measures only the sum of the currents flowing towards each of the paralleled buses without knowing how much current is flowing into each bus. The bus protection relay takes this into account by treating the double-bus as one single bus for the period of time that both isolators are closed for any breaker [3,4].

Breaker substitution is another switching strategy used in this case study. The goal is to isolate a breaker for maintenance while keeping a specific circuit energized. First, with the coupler closed, all other circuits are transferred to one bus (Bus #2 for example) by operating the appropriate isolators. The circuit of interest remains as the only circuit on the other bus (Bus #1). Next, protection of this circuit is provided by enabling substitute relays on the coupler breaker. These relays have CTs on the coupler breaker and are also wired to trip the same breaker. At this time, Bus #1 is part of the transmission circuit from the standpoints of both fault detection (CT) and isolation (CB). The breaker to be maintained is then bypassed by closing the bypass switch, after which disconnects are opened on each side of the breaker in question, to facilitate the work on it.

When the CT on this breaker gets by-passed, its measurements become incorrect (a current divider of an unknown and random division factor). The bus protection zone that uses that current (Bus #1) must therefore be inhibited. Note that differential protection on Bus #1 is not needed at this point, because the bus is already protected as a part of the circuit, by the substitute relays on the coupler breaker. Logic has been developed for the low-impedance bus protection relay, that automatically re-adjusts the bus protection zones of protection when the breaker by-pass switches are operated. During commissioning, bypass switches are operated on selected breakers to verify that the differential scheme is stable, and that the correct zone of protection is blocked. LEDs on the front of the relay indicate when a zone of protection is blocked.

Breaker failure (BF) detection is another important feature supported by the low-impedance bus differential protection and logic. When the breaker is bypassed, and substituted by the coupler, this feature is automatically switched to the coupler. In general, BF trips are always routed dynamically in order to trip the minimum zone required to isolate the failed breaker under any possible bus topology.

4. Scheme Configuration

The bus protection scheme for the double-bus single-breaker configuration in this case study, consists of seven relays mounted on two panels, test switches, terminal blocks, and an Ethernet switch for engineering access and SCADA communications (Figure 7).

Each phase relay is populated with modules supporting binary inputs, output contacts, and ac input cards, in order to match the needs of the application. Three relays are used to provide bus protection zones and BF overcurrent sensing for the three phases of the power scheme. The trip outputs also reside on these relays so that a bus fault can be cleared very fast, without the time delay involved in communicating the trip signal to another IED of the bus scheme. Typically these three relays are configured identically.

The fourth relay is configured to accept inputs from the bus isolator auxiliary contacts, and provide bus replica information for the phase relays. Dynamic association of currents to zones of protection is achieved by monitoring the status of each isolator connecting the circuit to either of the buses (Figure 8). Each isolator auxiliary switch is equipped with a pair of NO and NC contacts wired to the relay and used to provide the “opened”, or “closed” isolator position to the relay. Relay logic looks for discrepancies between these contacts, such as when both auxiliary contacts are opened, or both closed, and can be programmed to issue an alarm, to continue to run individual protection zones, to issue a signal inhibiting switching within the bus, or to provide for one overall (hence less-selective) zone of protection. The fifth relay is dedicated to BF timing and tripping.

The sixth relay is populated with only latching output contacts, which provide the physical isolation of the circuit breaker tripping circuits, replacing traditional cut-out/in switches. Output tripping contacts from the phase relays are wired in series with these latching contacts. Latching contacts are controlled from the seventh relay.

The seventh relay is used for remote control of the scheme, using 12 large programmable faceplate pushbuttons, and for SCADA interface. Bus Differential Tripping, Zone 1 Protection, Zone 2 Protection and Automatic Reclosing can be controlled from this relay.

All relays are connected via dedicated redundant rings of fiber-optic cable and exchange hundreds of digital signals to distribute bus status, logic, or indications (Figure 9). Note that this communication is isolated from the rest of the substation network. It is based on optimized protocol and dedicated hardware, and is not based on Ethernet. The Ethernet connection is for Engineering and SCADA access only.

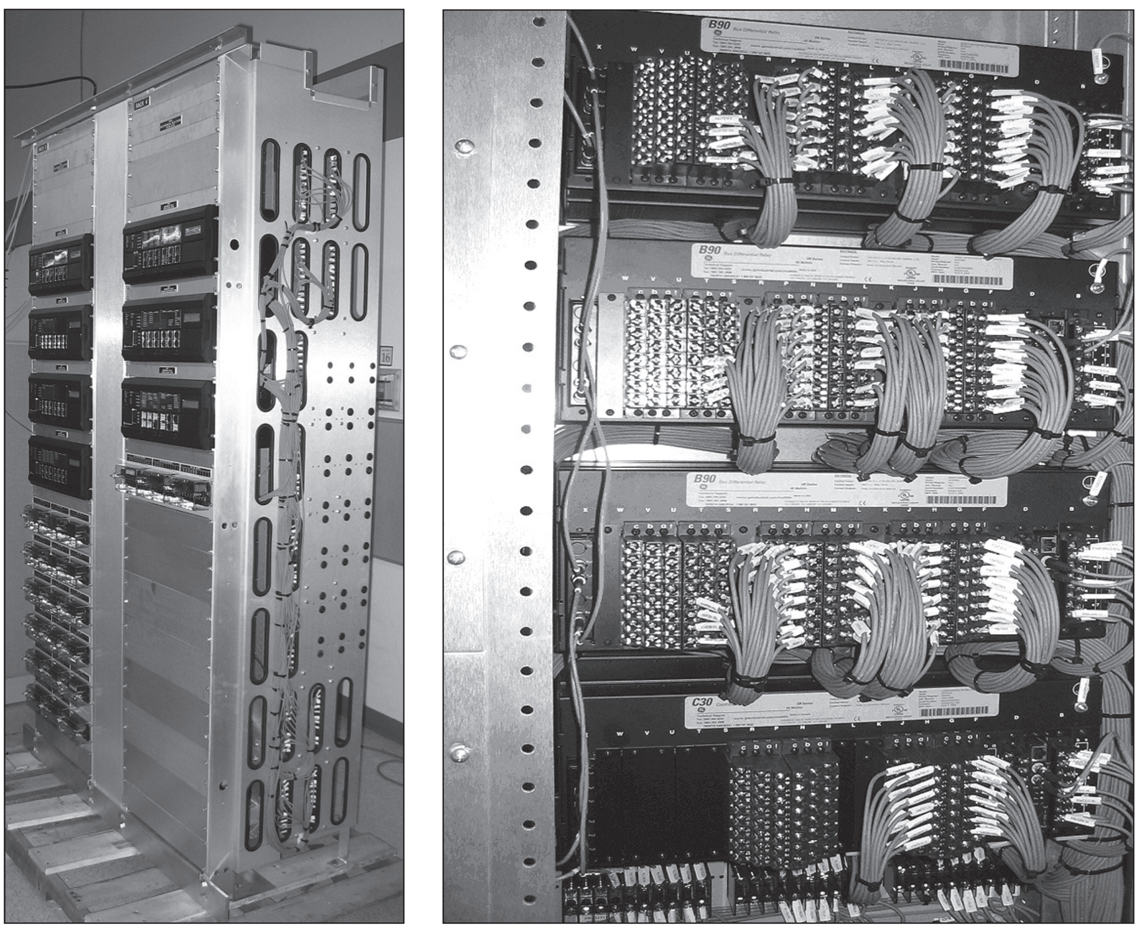


Fig 7.
Multi-IED phase-segregated bus scheme: allocation of functions and physical arrangement.

5. Commissioning Tests

Commissioning of bus protection schemes for such reconfigurable buses, requires good knowledge of the applied bus relays: inputs, outputs, protection, logic, indications, interfaces, and bus switching procedures, used by a given utility. Another very important aspect when commissioning, is the actual design and application of sufficient tests to prove all scheme components and logic.

5.1. Logic testing

A RTDS digital simulator was used for proof-of-concept testing of the unique scheme logic that was developed for the double-bus single-breaker bus protection scheme. Several scenarios were modeled to simulate bus switching under load conditions and to check for correct operation of the scheme under internal and external fault, and saturated CT, conditions.

5.2. Importance of testing auxiliary contacts of isolators

Proper testing and tuning of the isolator's auxiliary contacts is an important aspect of configuring and testing such bus protection schemes. Whether motorized or manual, isolators usually take a few seconds to move from one position to another. The same mechanism that moves the isolator main contacts changes the auxiliary contacts, but at slightly different times during the movement of the isolator main contacts

For example, to assure smooth insertion of the feeder circuit current into the bus differential zone, the auxiliary contacts are adjusted to read status "closed" at 75-80% of the isolator's travel distance, when the isolator is moved from open to closed. When the isolator is moved from closed to open, the auxiliary contacts are adjusted to change their state and read "open" at 35% of the travel distance, right after the main isolator contacts separate. The bus differential relay scheme is set to detect any auxiliary NO/NC contact pair discrepancy, issue an alarm, and optionally block bus switching, until the problem is fixed.

During isolator transitions, security of bus protection is ensured by the application of the check zone or undervoltage trip supervision, or both. However, it is necessary to ensure that the NO/NC auxiliary contacts perform reasonably well and do not generate unnecessary discrepancy alarms.

5.3. Polarity check of current transformers

One of the most important tests on the installed scheme is the CT's polarity check, as the chances of making wiring mistakes are proportional to the number of connections made.

First, the CT ratio and current contribution are checked for each bus circuit breaker by forcing secondary current from each circuit breaker to the respective relay inputs in order to assure a complete current circuit.

Next, with all tripping outputs disabled, the normal scheme load currents are allowed to flow through the bus differential scheme. The load currents are verified with a simple crosscheck of magnitudes and angles of currents as measured by the bus relay, and as measured by meters/relays in the individual circuits. A single bus potential is used as a common reference for the bus relay and feeder relays. In some cases the loading on one feeder circuit may be below the relay's minimum measurement threshold, making it impossible to validate the proper CT phasing of that circuit. This can usually be resolved by switching the power scheme to increase loading on that feeder circuit.

Lastly, the differential relay's metering function is used to check that no differential current is seen for each zone of the bus protection scheme, and that the restraint quantities are as expected. Even though absence of the differential current is a good indication of correct polarity, this check alone is not enough. It could happen that all the currents presently included in the zone have inverted polarities, and are therefore balanced for this particular topology, but would manifest problems when the zone boundary gets dynamically changed as the bus switches its circuits.

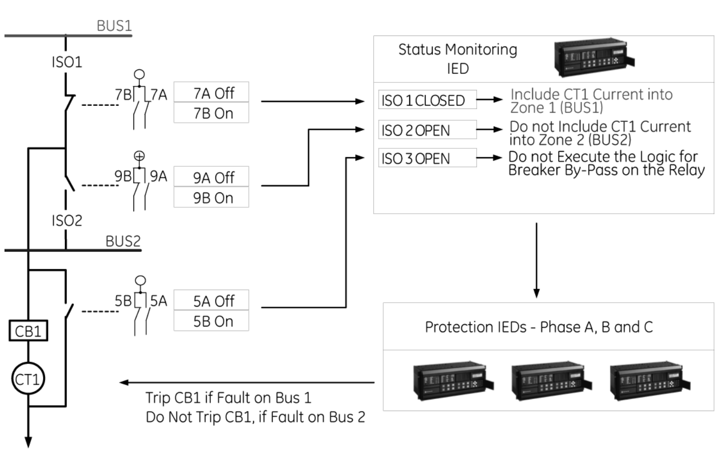


Fig 8.
Implementation of the dynamic bus replica.

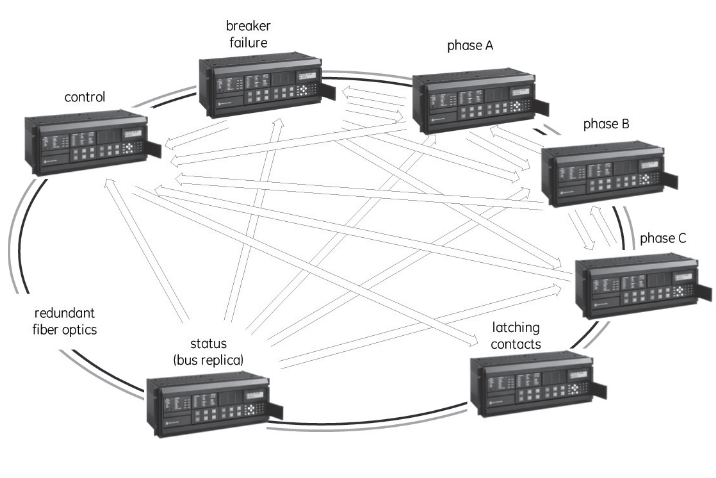


Fig 9.
Redundant Fiber Ring

5.4. Check of the transfer / paralleling logic

Normally each circuit is connected to only one of the two buses, and the scheme applies separate zones of protection for each bus. During the short period when transferring a circuit, the two buses cannot be protected individually. This particular application is developed to expand the two zones to cover the entire bus (Figure 10). For example, ISO1 and ISO2 closed simultaneously trigger the BUS 1 AND 2 PARALLELED condition. This in turn acts to include all circuit currents into both zones of protection. With the logic identical for all circuits but the coupler, all currents become part of zones 1 and 2 making the two zones identical. The coupler, in turn, is removed from both zones under the BUS 1 AND 2 PARALLELED condition (internal circulating current that must not be measured).

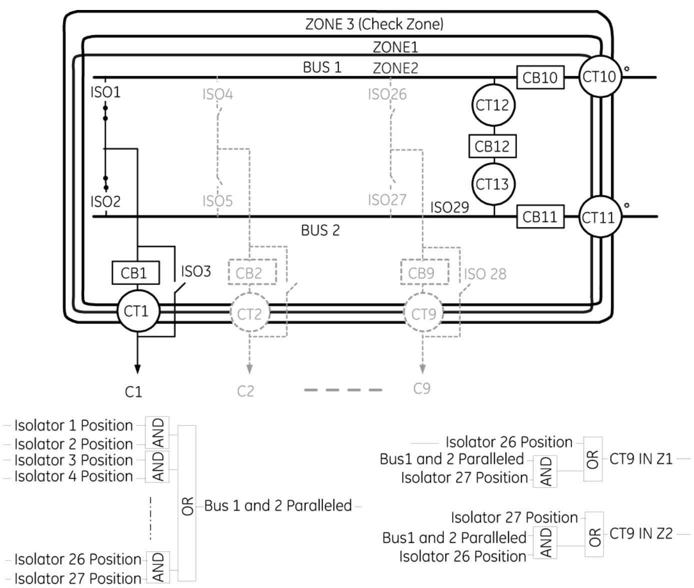


Fig 10.
Logic covering the case of paralleled buses when transferring a circuit.

The applied logic must be exercised during commissioning by transferring each circuit breaker from the preferred bus to the alternate bus and back again, thus checking both the operation of the scheme under load and the proper operation of the isolator auxiliary contacts.

5.5. Breaker by-pass and substitution

Figure 11 shows the breaker substitution case. Circuit C1 is transferred to the coupler (CT12, CB12). Its original breaker is bypassed by closing ISO 2. At this point zone 2 must be stopped because the CT12 and CT1 currents will not balance (CT1 is bypassed and measures a fraction of the current in the C1 circuit). This portion of the logic is checked by forcing the breaker substitution condition and examining the bus zone boundaries. These zone boundaries can be easily checked by reading the internal relay flags via PC software, or via LED indication on the relay faceplate [1]. During commissioning, one circuit breaker is set up to be bypassed on each bus in order to prove proper operation of the bypass switch auxiliary contacts and the relay logic.

6. Trip Tests and Verification of Voltage Supervision

Trip checks are performed on each zone of the bus differential by simulating an internal fault either by injecting test currents or by shorting out currents from the circuit with the greatest load and verifying that the proper circuit breakers are tripped. Coordination with voltage supervision is critical to making this test a success. At the same time as the fault is simulated, the bus voltage to the relay must be momentarily reduced below the voltage supervision pickup in order to get a trip output.

Individual zones for the two buses adjust constantly to the changing bus topology. For security, the check zone and an undervoltage condition "supervise" the trip signals originating at the bus protection zones. There are two reasons for this:

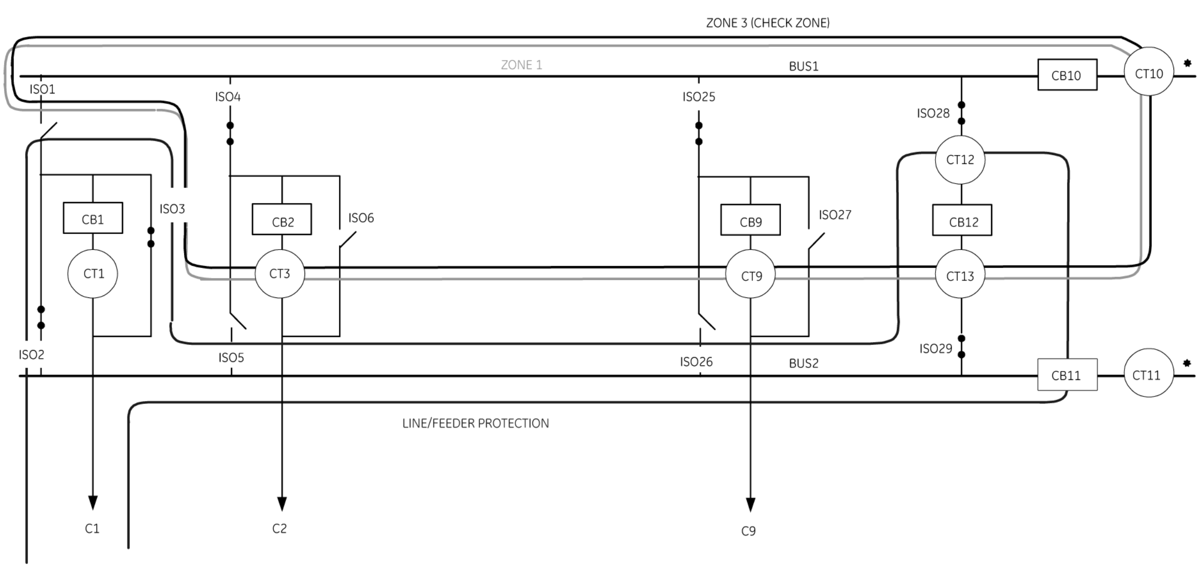


Fig 11.
Protection zones under breaker substitution.

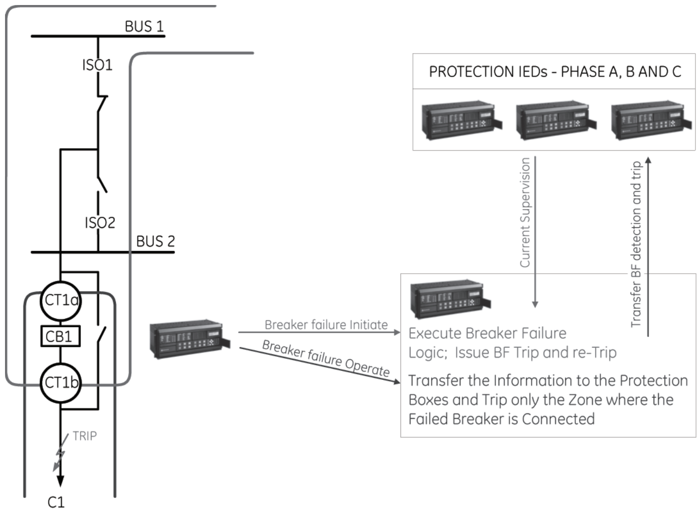


Fig 12.
Breaker Failure protection.

First, there are conditions in the logic that re-assign currents between the two zones of bus protection during switching. This is a necessary consequence of the response time of auxiliary contacts during switching, and the lack of "advanced" signaling by certain switching operations. The voltage supervision prevents false operation of the bus differential during these transitions.

Second, a CT problem condition may occur resulting in a wrong current reading if there is a problem in the main CT wiring, test switches or the input circuitry of the relay. In such a case, the voltage supervision blocks tripping and the relay can be set to alarm only, or block tripping of the affected zone.

The check-zone includes all the currents on the outer boundary of the entire bus. These currents are assigned permanently to say Zone 3. Zone 3 picks up conditions for any fault within the bus, and can release Zones 1 and 2 for operation. Zones 1 and 2 are responsible for selectivity and security. Zone 3 should have CT saturation detection or similar features disabled, as there may be a circulating current between input currents to the check zone. Circulating currents may fool features aimed at detecting CT saturation problem, and may thus inhibit operation during internal faults.

Undervoltage supervision uses bus voltage for security. Note that phase A protection is supervised from either AG, AB or CA voltage. Sometimes two sets of voltages must be wired to the relay and proper voltage must be selected for each of the two buses, to cover the case where the two buses are entirely isolated.

The tests described above are performed during commissioning to make sure that spurious pickup of the tripping zones is stopped by the check-zone and/or overvoltage condition (security). At the same time, both the check-zone and the undervoltage must be checked for dependability.

7. Breaker Failure Considerations

The microprocessor bus differential has logic built in to provide breaker failure protection with fault detectors and timers that can be set independently for each circuit breaker. In this particular case study an external BF function is used. With reference to Figure 12, the BF trip signal is issued by the line/feeder relay and is input to the bus protection scheme. The bus relay selects breakers that need to be tripped to isolate the problem, based on the bus topology at that moment.

A second BF function, integrated with the bus relay, is used for bus faults. The BF is initiated from the 87B function and sent to the line/feeder BF relays in order to force the re-trip and provide for redundancy of the BF function.

Commissioning tests include simulation of breaker failure for each circuit by closing the corresponding BFI and External BF contact inputs to the bus differential scheme, and verifying that the trip contacts trip only the breakers connected to the same bus as that of the failed breaker.

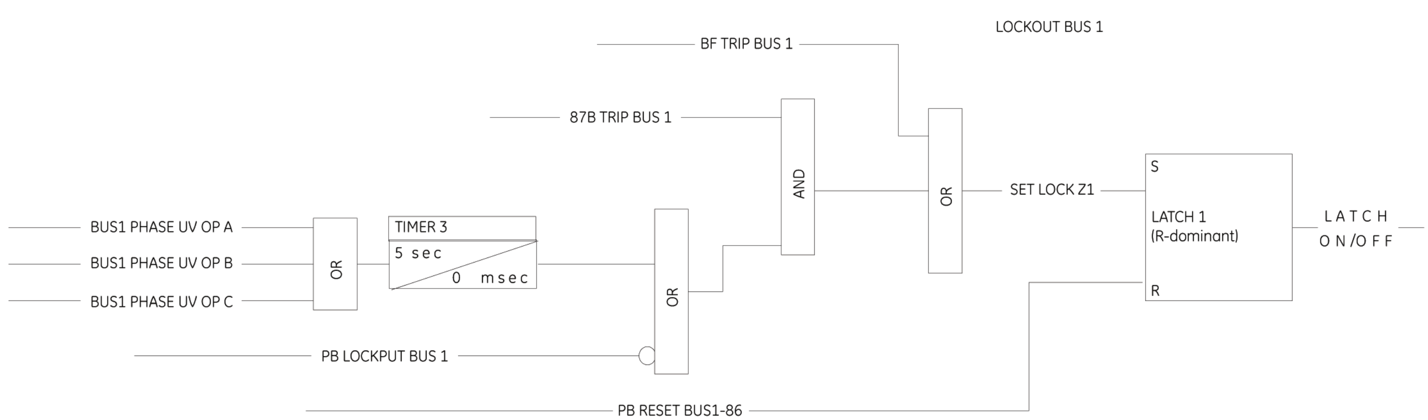


Fig 13.
Lockout logic

8. Lockout and Reclose Block Functionality

The scheme incorporates internal lockout logic to block auto reclose of the bus following a permanent bus fault or breaker failure operation. A combination of a software feature (non-volatile latch) and NC output contacts is used to implement this feature. The logic includes a feature to enable/disable auto reclose by one breaker in order to test the bus following a bus fault. If this test is unsuccessful, further auto reclose actions are blocked by the lockout relay.

Figure 13 presents the applied logic. Based on this solution, the lockout will not be initiated when the first bus fault occurs unless the test is eliminated. If a second fault occurs after the scheme has detected undervoltage for at least 5 seconds, the lockout will be set. This feature can be enabled or disabled by the operator and is tested during commissioning by simulating an auto reclose operation.

9. Pushbuttons

This microprocessor relay design uses pushbuttons in place of conventional control switches, to enable and disable (a) bus protection, (b) breaker failure protection on each breaker and (c) auto reclose following a bus fault. This design simplifies both wiring and overall design of the scheme and allows the substation operator to control the scheme from one location, such as a control building, if the protective relays are installed in a remote location.

10. Self-Monitoring

Microprocessor relays have a great advantage over electromechanical relays because they are self-monitoring. Each microprocessor relay in the bus differential scheme has its typical self-monitoring features and provides an alarm for critical failures such as failure of the processor or power supply. In addition, alarms are provided for communication failures between relays, for disagreement between the auxiliary contacts on the isolator and bypass switches, and for failure of a CT. This last one is very important since it can identify a failed CT before the scheme is called on to operate for a bus fault. A high impedance relay scheme can fail to operate due to a CT failure and this scheme has no way of detecting this type of failure. Each of these alarm conditions is tested as part of commissioning.

11. Operator Training

Operator training was provided as part of the final testing and commissioning of the microprocessor bus differential relay scheme, because of the significant differences between it and the previous high-impedance differential design. One major difference is that the new scheme has essentially no relay switches for the operator to switch while switching is being performed on the bus isolators. Previously, the operator was required to manually operate one control switch to connect the two bus differentials prior to switching the bus, and to manually operate another switch for each breaker being switched to match the position of the isolators on the bus. In addition, the operator had to manually take the scheme out of service and place it in test mode after switching, in order to confirm that the differential was balanced prior to disabling the relay. Operators also need to understand how to interpret the LED status and relay alarm indicators, and how to operate the pushbuttons to enable tripping and automatic reclosing.

12. Conclusions

Modern bus protection solutions may be developed as multi-IED phase-segregated schemes. They are built on standard software and hardware platforms, resulting in significantly lower costs compared with first-generation microprocessor-based bus relays, and providing a high degree of user familiarity, initial product maturity, and flexibility of application [1]. Application of these relays to reconfigurable and relatively complex buses can be done in user-programmable logic allowing accommodation of various protection philosophies, greater flexibility, and "future proofing." Modern relays support remote access, enhanced faceplate indicators, metering, oscillographic recording and other features that facilitate testing and commissioning as well as provide a record of scheme faults. This case study shows that a complex bus application, pre-tested at the factory (Figure 5), can be commissioned within a 2 to 3-day time period.

Built in logic allows operators to perform routine switching of the bus without the need for manually operating relay control switches, thus saving time and eliminating the possibility of incorrect operation.

13. References

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