Commissioning and Testing Complex Busbar Protection Schemes - Experience at Pacific Gas & Electric

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1. INTRODUCTION

As “junction points” present at all voltage levels and carrying energy in electric power systems, power substation buses are critical to system topology. Exposure to high fault currents imposes stringent performance requirements on both bus protection relays and current transformers. Saturation of current transformers (CTs) during external faults may jeopardize the security of bus protection due to unbalanced currents in the differential relay. Misoperation of a bus relay, in turn, considerably changes system topology and significantly impacts both power delivery in the case of a distribution bus, and system 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 scheme for these buses has been a high impedance bus differential relay. The single breaker double bus configuration 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 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 systems have provided a better solution to protecting the double-bus single breaker bus configuration. Such systems monitor all currents and positions of breakers and isolators, and dynamically adjust their zones of protection for 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. These systems can also be installed in outdoor cabinets in proximity to the protected bus reducing the length of CT wiring to the differential relays (Figure 2).

![Fig.2. 60kv bus with outdoor relay cabinet and indoor control building.](image)

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

Last but not least, the installation a low impedance differential makes it easier to accommodate added generation or expansion of existing buses because it is not necessary to changing existing CTs or add slip-on CTs as may be required for the high impedance bus differentials.

The performance of a high impedance bus differential requires that all CTs have the same ratio, preferably not a tapped CT winding, and similar excitation characteristics. Traditionally robust high-impedance schemes may misoperate if all of the CTs are not...
properly matched. Modern low-impedance solutions show very high immunity to extreme cases of CT saturation, in many cases it is better than the high-impedance schemes [2].

A low-impedance microprocessor-based relay is a complex piece of protection equipment to commission. Quite often the scheme would have tens of ac current inputs, several ac voltage inputs, tens of trip outputs, and tens, if not hundreds, status inputs.

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

2. **Cost-Efficient Bus Protection Schemes**

While monitoring of the bus configuration is not important for many bus arrangements (Figures 3 and 4), for other configurations monitoring the bus topology and following it in terms of measuring and tripping zone boundaries is a must (Figure 5).

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

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

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From the perspective of the main protection, the bus differential function (algorithm) is naturally phase-segregated. This means that no information is required regarding currents in phases B and C in order to fully protect phase A. This bears two key consequences and advantages [2-4]:

- First, completely independent microprocessor-based devices could 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.
- Second, sampling synchronization is not required between the separate microprocessor-based relays that process signals from individual phases.

The above observations facilitate phase segregated busbar protection. With reference to Figure 6, three separate relays (Intelligent Electronic Devices, IEDs [1]) are used to provide protection for a three-phase busbar. Each device is fed with its own ac currents and voltages that belong to the same phase, processes these signals, and arrives at the trip/no-trip decision. 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 tripping/restraining action.

Modern relays [1,2] sample their input signals relatively fast – at 64 samples per cycle, or faster – and therefore are capable of incorporating sophisticated and robust means to deal 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 sectionalizing breakers dividing bus sections (Figure 5a). In addition, each feeder circuit breaker is equipped with a by-pass switch. The by-pass 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 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/from the applied differential zones. Allocation of trip commands to individual breakers follows this dynamic bus image. The same applies to the 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 be transferred from one bus to the other, the isolator switch connecting the circuit to the target bus is closed, and afterwards 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 case fault occurs at this time, the faulted bus cannot be separated from the other bus (no breaker, but two isolators connected in series). Also, the relay cannot identify the faulted bus (Bus #1 or Bus #2?) as the CT associated with the transferred circuit measures the sum of the currents flowing towards each of the paralleled buses without the ability to know how much 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 the 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 is left 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 moment, Bus #1 is part of the transmission circuit from both fault detection (CT) and isolation (CB) points of view. Next, the breaker to be maintained is by-passed by closing the bypass switch, and last, disconnects are opened on each side of the breaker to facilitate the work on it.

When the CT on the breaker gets by-passed, its measurement is incorrect (a current divider of an unknown and random division factor). Therefore, the bus protection zone that uses that current (Bus #1) must be inhibited. Note that differential protection on Bus #1 is not needed now because the bus is already protected as a part of the circuit by the substitute relays on the coupler breaker. Logic was developed for the low impedance bus protection relay to automatically re-adjust 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 the correct Zone of protection is blocked. LEDs on the front of the relay indicate when a zone of protection is blocked.

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

4. **System Configuration**

The bus protection system 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 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 system. The trip outputs also reside on these so that a bus fault can be cleared very fast without the time delay required to communicate 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 the 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, issue a signal inhibiting switching within the bus, or 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 only with 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 it not based on Ethernet. The Ethernet connection is for engineering and SCADA access only.

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**Fig. 8. Implementation of the dynamic bus replica.**

5. Commissioning Tests

Commissioning of bus protection system 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 system 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 during internal and external faults 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 these bus protection schemes. Whether motorized or manual, isolators usually travel few seconds from one position to another. The same mechanism that moves the isolator main contacts changes the auxiliary contacts, but at slightly different times during travel 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 isolators travel distance, when the isolator is moved from opened to closed. When isolator is moved from closed to opened, the auxiliary contacts are adjusted to change their state and read “opened” at 35% of the distance, right after the main isolator contacts depart. The bus differential relay system 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 transitions of the isolator, 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 system is the CTs polarity check, as the chance 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 to assure a complete current circuit.

Next, with all tripping outputs disabled the normal system load currents are allowed to flow through the bus differential system. 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 system to increase loading on that feeder circuit.

Last, 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 for correct polarity, this check alone is not enough. It could happen that all the currents presently included in the zone have inverted polarities, and therefore are balanced for this particular topology, but would show problem when the zone boundary gets dynamically changed as the bus switches its circuits.

5.4. Check of the transfer / paralleling logic

Normally each circuit is connected only to one of the two buses, and the scheme applies separate zones of protection for each bus. During the short period of 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 toward including all circuit currents into both zones of protection. With the logic identical for all circuits but the coupler, all currents become a 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).

The applied logic must be exercised during commissioning by transferring each circuit breaker from the preferred bus to the alternate bus and back again, checking 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 presents the breaker substitution case. Circuit C1 is transferred to the coupler (CT12, CB12). Its original breaker is by-passed by closing ISO 2. At this point
zone 2 must be stopped because the CT12 and CT1 currents will not balance (CT1 is by-passed 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. 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 to prove proper operation of the bypass switch auxiliary contacts and the relay logic.

![Diagram of bus differential protection logic](image)

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

### 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 shorting out currents from the circuit with the greatest load and verifying the proper circuit breakers are tripped. Coordination with the voltage supervision is critical to making this test a success. At the same time 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 supervision:

First, there are race conditions in the logic that re-assigns 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 of certain switching operations. The voltage supervision prevents false operation of the bus differential during these transitions.

Second, a CT trouble 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 this 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 for any fault within the bus, and would release zones 1 and 2 for operation. The Zones 1 and 2 are responsible for selectivity and security. Zone 3 shall 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 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 when 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 undervoltage shall 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 presented 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 is send 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 the failed breaker.

8. Lockout and Reclose Block Functionality

The scheme incorporates internal lockout logic to block auto reclose on 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 to test the bus following a bus fault. If the 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 cut out. 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 cut in and cut out the bus protection, to enable or disable breaker failure protection on each breaker and to enable or disable the auto reclose following a bus fault. This design simplifies 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 the 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 communications failure between relays, for disagreement of 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 that scheme has no way to detect this type of failure. Each of these alarm conditions is tested as part of commissioning.

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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 from 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 done on the bus isolators. Previously, the operator was required to manually operate one control switch to connect the two bus differentials together prior to switching the bus, and to manually operate another switch for each breaker that was 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 a test mode after switching in order to confirm that the differential was balanced prior to cutting the relay in service. Operators also need to understand how to interpret the LED status and alarm indications on the relays 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 yielding significantly lower cost compared with first generation of microprocessor-based bus relays, 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 indications, metering, oscillography recording and other features that facilitate testing and commissioning as well as provide a record of system faults.

This case study shows that a complex bus application, pre-tested at the factory (Figure 5), can be commissioned within a 2-3 day time period.

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

REFERENCES


BIOGRAPHIES

Lubomir Sevov received his MSc degree from Technical University of Sofia, Bulgaria in 1990. After his graduation, he worked as a protection and control engineer for National Electric Company (NEC) Bulgaria. Mr. Sevov joined GE Multilin in Markham, Ontario in 1998 as a relay test design engineer. In 2001 he joined the research and development team as an application engineer. Lubo is an IEEE member, and a registered professional engineer in the province of Ontario.

Bogdan Kasztenny holds the position of Protection and System Engineering Manager for the protective relaying business of General Electric. Prior to joining GE in 1999, Dr. Kasztenny conducted research and taught protection and control at Wroclaw University of Technology, Texas A&M University, and Southern Illinois University.

Between 2000 and 2004 Bogdan was heavily involved in the development of the Universal Relay™ series of protective IEDs, including a digital phase-segregated bus differential relay.

Bogdan authored more than 140 papers, is the inventor of several patents, Senior Member of the IEEE, and the Main Committee of the PSRC.

In 1997, he was awarded a prestigious Senior Fulbright Fellowship. In 2004 Bogdan received GE’s Thomas Edison Award for innovation.

Ed Taylor received his MSc in EE Power Engineering from the University of Santa Clara in 1981. He is a registered engineer in the State of California, a Member of IEEE PES, member of WECC Relay Work Group, and currently holds the position of Principal Protection Engineer with Pacific Gas and Electric Company in Oakland, California. Ed has over 39 years of experience in System Protection in the utility business.