Low-Impedance Bus Differential – Security and Reliability in Complex Bus Arrangements

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LOW-IMPEDANCE BUS DIFFERENTIAL – SECURITY AND RELIABILITY IN COMPLEX BUS ARRANGEMENTS

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Abstract

The concentration of electric power at system buses adds to both the need for high-speed tripping in case of faults and the need to avoid false tripping in case of external faults. This combined need for both superior dependability and security has led to many enhancements and system modifications in bus protection.

Bus configurations with multiple zones are particularly difficult to provide with dependability and security to meet system needs. Zone switching, bypass breakers, and transfer buses all contribute to protection system complexity. Addressing this complexity in a protective relay requires both measuring elements and logic that can operate with the speed necessary for system stability.

This paper details how security and dependability are addressed in a low-impedance relay. The characteristics of zone switching, current transformer location during breaker bypass, and transition transients are addressed. Reliability and security of low-impedance systems are compared to distributed and high-impedance protection schemes. Conclusions on speed requirements and impacts on protection are presented.

1 Introduction

Most primary elements of the power system are well defined, with the exception of power line tower construction and busbar layouts. Whereas tower designs constantly evolve with new designs to reduce losses and cost, the choice of busbar layout is based on voltage level, size of the station, and operational requirements. We can categorize busbar layouts using different criteria, but from a protection point of view, one of the most complex busbar layouts to protect is a dynamically switched, multizone scheme with transfer capabilities and inboard current transformers (CTs).

2 Principle of busbar protection

Kirchhoff's current law states that the sum of current flowing into a point is zero. Applying this law to busbar protection, the current flowing toward the busbars must again flow away from the busbars so that the sum is zero. If the sum is not zero, the busbar protective relay declares a system fault and trips all circuit breakers connected to the faulted busbar.

3 Security during through-fault and CT open-circuit conditions

With the integration of modern power systems, fast clearance of busbar faults is crucial to limit damage to equipment and to maintain system stability. Furthermore, the high fault levels of an integrated power system cause extremely high fault current to flow, which could result in severe CT saturation that can cause busbar protection to misoperate for through faults. To be secure and avoid misoperation for through faults, busbar relays are usually desensitized once a through fault is determined [1]. Fig. 1 shows one method to distinguish between internal and external faults. During internal faults, both operating and restraint currents increase, whereas for external faults without CT saturation, only the restraint current increases.

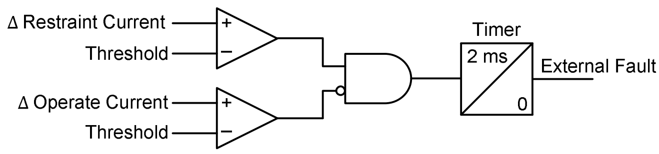

Fig. 1. External fault detection logic.

The top input into the AND gate in Fig. 1 changes to logical 1 when a change in restraint current exceeds the threshold setting. If there is no corresponding change in the operating current (bottom input of the AND gate remains logical 0) for 2 milliseconds, the timer expires, indicating an external fault.

Fig. 2 shows the characteristic of a dual-slope busbar protective relay characteristic. The relay normally operates at the Slope 1 setting but switches to Slope 2 when the logic in Fig. 1 detects an external fault. When operating at the Slope 2 setting, the relay is secure during through faults, even when CT saturation occurs.

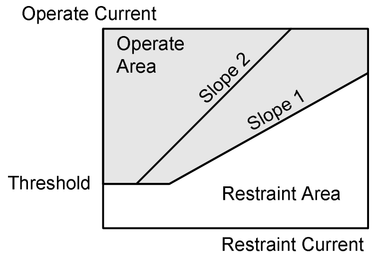

Fig. 2. Dual-slope characteristic.

When a CT opens, there is an incremental increase in the operating current and a corresponding incremental decrease in the restraint current. The two increments should result in a summation equal to zero. Fig. 3 shows the open CT detector logic. The change in operating current, the change in restraint current, and the operating current are the analog inputs to the logic.

A CT open circuit is declared when the change in operating current is greater than or equal to 0.05 per unit (pu), the change in restraint current is less than –0.05 pu, the sum of these two values is less than 0.05 pu, and the operating current is greater than or equal to a threshold. The logic resets when the operating current is either less than 90 percent of a threshold or less than 0.05 pu.

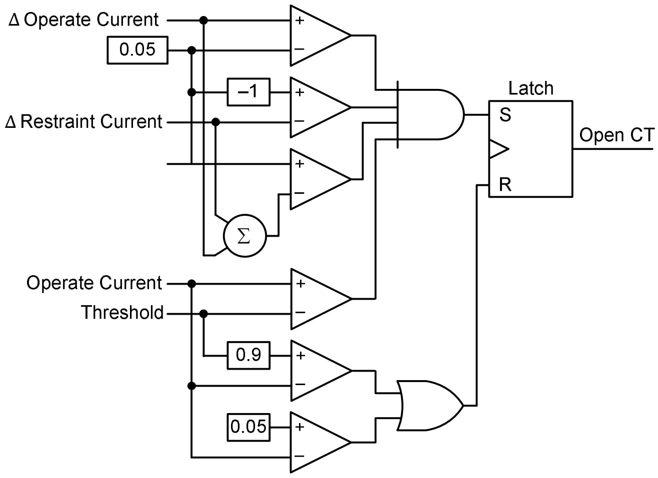

Fig. 3. Zone-specific open CT detector.

The operation of the open CT detector logic is fast enough to assert before the differential element gives a trip output. By using this logic to supervise the differential element, the scheme can be blocked during CT open-circuit conditions.

4 Multiple zones and dynamic zone selection

Multiple bus zones provide a method to reduce the impact of busbar faults on the system. For example, if a station is divided into four zones, only 25 percent of the station is lost when a busbar fault occurs in any one of the four zones.

To allow operational flexibility, modern busbar protective relays dynamically reassign input currents to appropriate differential elements when the station configuration changes. Link (and, in certain cases, circuit breaker) auxiliary contacts provide station configuration information in the form of contact inputs wired to the busbar protective relay. By evaluating the status of the auxiliary contacts, the relay dynamically assigns (dynamic zone selection) the currents to the appropriate differential elements.

Although dynamic zone selection provides operational flexibility, there are instances that can cause misoperations.

Of particular concern are instances when more than one link of any terminal is closed at the same time. When this happens, parallel paths form, possibly resulting in the unbalance of multiple zones, as shown in Fig. 4a and Fig. 4b [3].

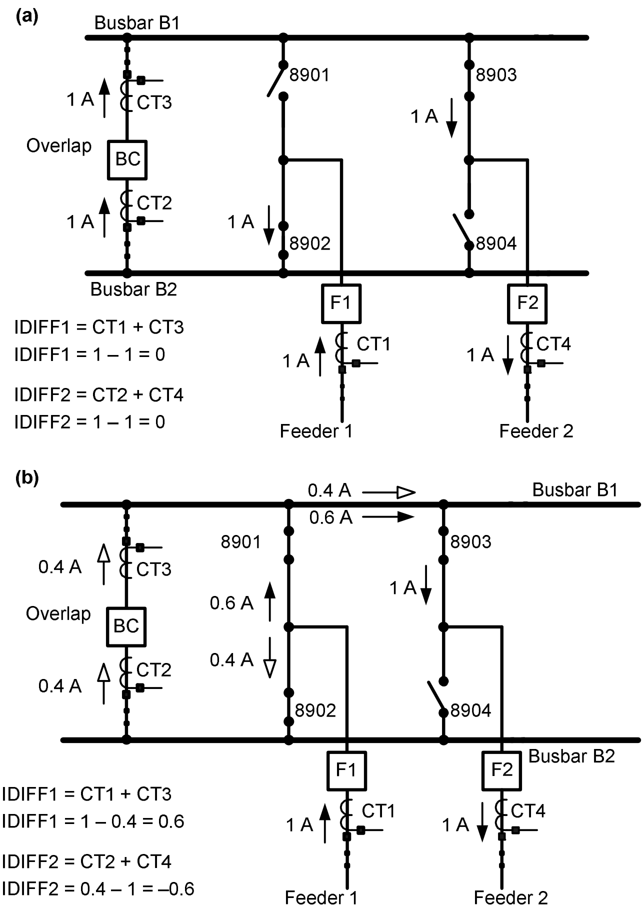

Fig. 4. (a) Both elements balanced. (b) Both elements unbalanced.

Fig. 4a shows a double busbar layout in which two links can be closed simultaneously (8901 and 8902, for example). With the bus coupler breaker (BC) connected in overlap, CT1 and CT3 form Differential Element 1 (IDIFF1) and CT2 and CT4 form Differential Element 2 (IDIFF2). There are no parallel paths in Fig. 4a, and the differential current in both differential elements is practically zero.

Fig. 4b shows the operating condition where both links of Feeder 1 (8901 and 8902) are closed. Closing Link 8902 when Link 8901 is closed forms a parallel path between the two busbars, and both differential elements become unbalanced. Fig. 4b shows the resulting differential currents during this unbalance (assuming an arbitrary 60/40 percent current distribution).

To prevent misoperation when parallel paths form, combine the parallel paths into a single zone and route the CTs to a single differential element. Referring to Fig. 4b, after merging the two bus zones to form a single zone that includes CT1 and CT4 (but not CT2 and CT3), current in this single zone sums to zero and no misoperation occurs.

5 Link main contact and auxiliary contact timing

Successful merging of the zones depends solely on proper timing coordination between the link main and auxiliary contacts. Fig. 5 shows the link auxiliary contact requirements with respect to the arcing point. The position of 0 percent travel indicates the position when the main contacts are fully open, and the 100 percent position indicates when the main contacts are fully closed.

For the busbar protection scheme to work properly, the CTs must be assigned to the appropriate differential element before current flows (the arcing point) in an open-to-close link operation. Likewise, the CTs must remain assigned to the appropriate differential element for as long as current can flow in a close-to-open operation.

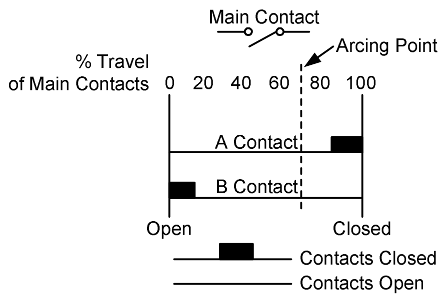

Fig. 5. Link auxiliary contact requirements with respect to the arcing point for an open-to-close link operation.

Successful implementation of these requirements can be achieved with only a normally closed (B-type) auxiliary contact by applying the principle of (1).

$$(\text{link})\ \text{NOT OPEN} = (\text{link})\ \text{CLOSED} \tag{1}$$

Using this principle, the relay properly coordinates the primary current flow and the CT current assignment to the appropriate differential element. Table 1 shows the four possible disconnect auxiliary contact combinations and the way the relay interprets these combinations.

Case	**89A**	**89B**	**Status**
1	0	0	Closed
2	0	1	Open
3	1	0	Closed
4	1	1	Closed

Table 1: Disconnected A and B auxiliary contact status interpretations.

6 Second trip criterion – check zone protection

Link auxiliary contacts sometimes misalign or fail, resulting in incorrect input current to differential element assignment. To prevent misoperations in such cases, many schemes use a second trip criterion to supervise the zone-specific element.

An example is to use voltage elements for this supervision. One disadvantage of using voltage elements as a second criterion is that voltage elements just indicate the presence of a fault on the power system—this fault can be anywhere on the power system, not necessarily on the busbars.

A method that specifically indicates a busbar fault is the check zone. The check zone uses the same principle as the zone-specific elements but encompasses the whole station. It is really just one big zone that by definition is independent of any link auxiliary contacts. The check zone also excludes the bus coupler CTs. If a link auxiliary contact now fails, the zone-specific element can operate without any action from the check zone element (because the check zone is independent of the link auxiliary contacts). For the scheme to give a trip output, both the zone-specific element and the check zone element must assert, as Fig. 6 shows.

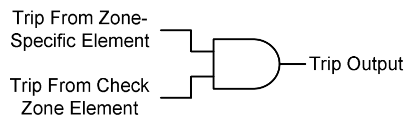

Fig. 6. Two-out-of-two trip—the check zone supervises the zone-specific element.

The two-out-of-two tripping logic in Fig. 6 provides busbar protection security should link auxiliary contacts misalign or fail.

7 The impact of CT positions

In general, CTs are either installed as a separate item (free-standing CTs) or within transformer or circuit breaker bushings (bushing CTs). Bushing CTs have a considerable cost benefit over free-standing CTs but significantly impact busbar protection in schemes that use a transfer facility and a check zone.

Inboard and outboard CTs refer to the position of CTs relative to the line link. An inboard CT is not in circuit when a feeder is on transfer (Link F1TL is closed and Link F1LD is open in Fig. 7a). With the same linking, the CT in Fig. 7b is in circuit with an outboard CT.

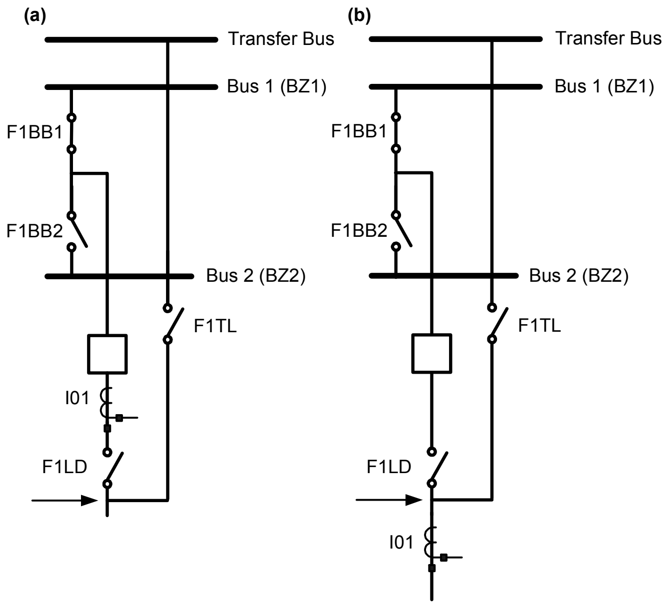

Fig. 7. (a) Inboard (bushing) CT. (b) Outboard CT.

7.1 Inboard CT, zone-specific protection

Because the line CT is not available, a separate zone for the transfer busbar cannot be formed, and the line protection also protects the transfer busbar. To balance the zone-specific element, remove one of the bus coupler CTs when a bay goes on transfer.

7.2 Inboard CT, check zone protection

In the case of inboard CTs, the permanently out-of-circuit line CT makes balancing the check zone impossible. The solution is to make the check zone configurable. Those who prefer to have the check zone independent of the link auxiliary status may disagree with this solution, but the solution applies only for the instance when a line is on transfer, making it a low-risk compromise.

Fig. 8a shows an example of a check zone with inboard CTs. In Fig. 8a, Feeder 1 connects to Bus 1 (the line is not on transfer). Under these conditions, Zone 1 (formed by I01 and I03), Zone 2 (formed by I02 and I04), and the check zone (formed by I01 and I04) are all balanced.

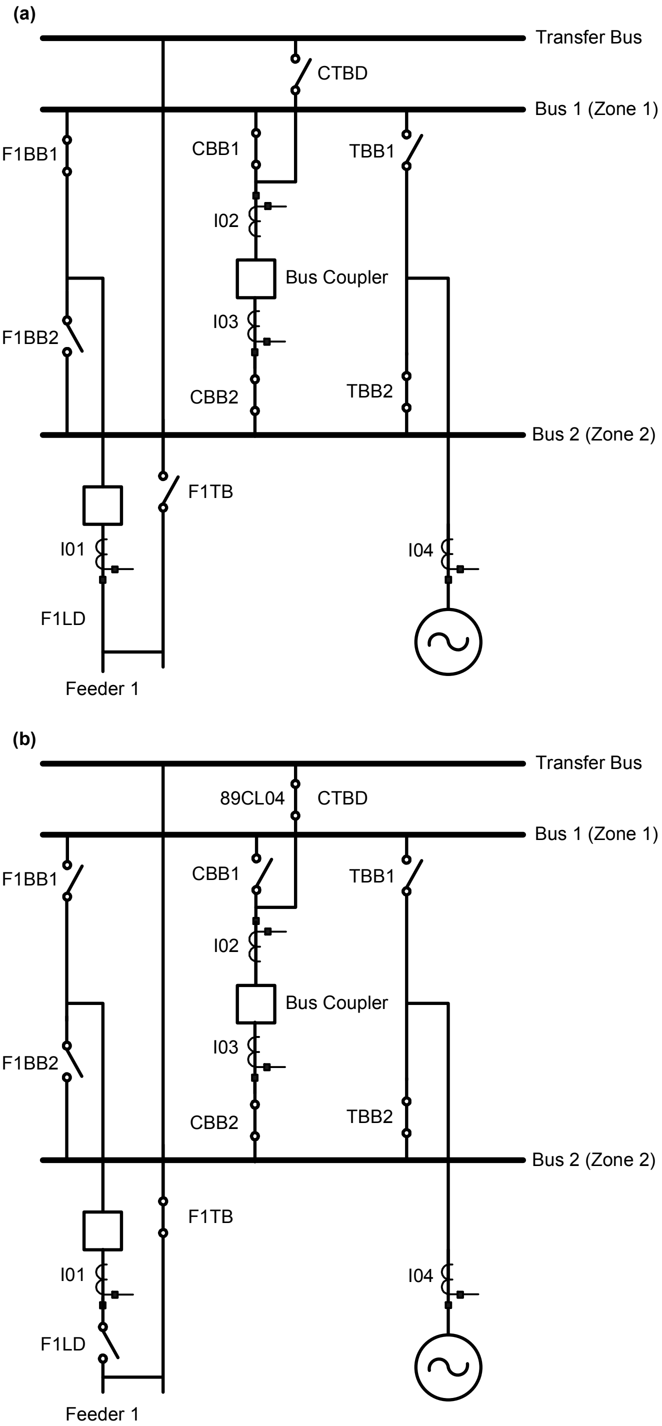

Fig. 8. (a) Normal operating conditions. (b) Feeder 1 on transfer.

In Fig. 8b, Feeder 1 connects to the transfer busbar. When Feeder 1 connects to the transfer busbar, note the following conditions:

- Line CT I01 of Feeder 1 is no longer in the circuit.
- Without I01, the current to balance I03 is missing, resulting in an unbalanced Zone 1.
- Without I01, the current to balance I04 is missing, resulting in an unbalanced check zone.
- I02 and I04 are still available, so Zone 2 is balanced.

To balance Zone 1, we need to remove I03 from the Zone 1 differential element calculations. To balance the check zone, we need to add I02 to the check zone differential element.

8 Comparison of reliability and operating times in protection schemes

Low-impedance differential schemes, both centralized and distributed, can accommodate zone switching. Consider the logic of Fig. 6 as it applies to tripping time. As long as the check zone operates as quickly as the zone-specific element, there is no delay in tripping time but the check zone dramatically improves scheme security.

The reliability of the bus protection is strongly impacted by the topology of the system [2]. Consider the fault tree of Fig. 9.

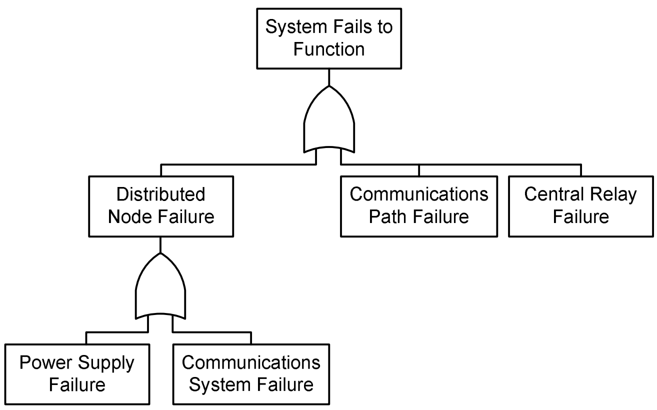

Fig. 9. Simplified fault tree for bus protection system.

For any system, the top failure event, failure of the system to function, represents the overall failure rate and equals the sum of the failure rates of the individual components. For a centralized system, the overall failure rate is the failure rate of the central relay plus the failure rate of the communications channel from the CT.

For a distributed system, the overall failure rate is the sum of the failure rates of each distributed component, such as the power supply, analog-to-digital (A/D) converter, and communications system, plus the failure rate of the central system. If the power supply of each node, for example, has a failure rate of one-third that of the central unit and there are 15 nodes (each with an individual power supply), the system failure rate will be six times larger for a distributed system than a centralized system. This illustrates why extreme care must be taken to ensure distributed components are ultrareliable.

9 Conclusion

Experience with many different types of bus protection systems over the course of years has led to the following solutions that address known concerns:

- Zone switching logic must consider transients during switching to maintain security.
- A check zone, independent of link auxiliary contacts, adds security without increasing tripping time or scheme complexity.
- Advanced logic can prevent misoperation during open CT conditions.
- CT location must be considered in view of operational requirements.

Considering the potential failure characteristics of a given scheme will reduce misoperations while maintaining reliable tripping. Using all the measurements and logic capabilities of modern microprocessor-based relays addresses scheme weaknesses without compromising speed.

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