MODERN COST-EFFICIENT DIGITAL BUSBAR PROTECTION SOLUTIONS

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1. Introduction

Simple busbars with dedicated Current Transformers (CTs) could be efficiently protected by the high-impedance principle – a fast and reliable scheme with tens of years of excellent field record. However, new power generation added recently, or to be added in the near future, complicates historically simple busbar arrangements and exposes existing CTs to saturation due to increased fault current level. New substations are often designed to satisfy cost requirements rather than keep the protection task straightforward and easy. This results in complex busbar arrangements.

High-impedance busbar protection principle faces major problems when applied to complex busbar arrangements. Quite often, the zones of protection are required to adjust their boundaries based on changing busbar configuration. This calls for switching secondary currents – an operation that is never considered safe and should be avoided whenever possible.

Digital low-impedance busbar protection schemes are ideal for complex busbars. Optimal zoning (dynamic bus replica) is achieved naturally by switching currents in software, i.e. by making logical assignments to multiple zones of protection while keeping physical currents uninterrupted. Other benefits include integrated breaker fail protection, communications, oscillography, sequence of events recording, multiple setting groups, and other natural benefits of the digital generation of protective relays.

Till very recently digital busbar and breaker failure protection schemes for medium-size and large busbars were not attractive to users traditionally biased toward the high-impedance approach. There used to be several reasons for that. Schemes available on the market were very expensive, difficult to apply, considerably slower as compared with the high-impedance protection, and perceived less secure. All these factors have changed recently. Modern digital relays are much faster, use better algorithms for security, and became affordable after introduction – in late 2001 and early 2002 – of a phase-segregated microprocessor-based busbar relay.

Major hardware, architectural and processing power challenges facing a digital protection system for medium-size and large busbars are:

(a) Large number of analog signals needs to be processed (tens of currents, few voltages). The problem is how to bring all the required signals into a “box”.

(b) Large number of digital inputs may be required to monitor isolator and breaker positions in order to provide for the dynamic bus replica mechanism (dynamic adjustment of zone boundaries based on changing busbar configuration).

(c) Large number of trip-rated output contacts may be required particularly in the case of reconfigurable busbars when each breaker must be tripped separately depending on bus configuration at the moment of tripping.

(d) Several differential zones are required to cover individual sections of a large bus. This calls for significant processing power of the hardware platform.

Traditionally, the aforementioned problems of large number of inputs and outputs, resulting power supply requirements, and the processing power requirements have been addressed by two distinctively different architectures: distributed or centralized. Both the solutions require large quantities of specialized hardware. As a result, they are difficult to engineer, face certain dependability and reliability problems, do not have a chance to mature due to comparatively low volume of installations, and are very expensive.

The new solutions that emerged recently address the above problems by targeting medium-size busbars only and using generic hardware platforms (such as multi-winding or small bus relays) to build a phase-segregated, cost-efficient, easy-to-engineer busbar relays.

This paper focuses on the new phase-segregated solution and is organized as follows.

First, a general overview of busbar protection principles is given starting from simple interlocking schemes for single-incomer distribution busbars, to high-end microprocessor based protection schemes.

Second, a novel, phase-segregated approach based on existing hardware platforms capable of processing plurality of single-phase AC input signals, is presented. The new solution is discussed in details including architecture, reliability, dependability, speed of operation, security on external faults, ease of configuration, and cost.

Third, basic application principles for protection of complex busbars are presented. They include a tie-breaker with a single CT, treatment of blind zones and over-tripping zones, dynamic bus replica, end fault protection and breaker failure protection. Both principles and examples are presented.

2. Busbar Protection Techniques

Power system busbars vary significantly as to their size (number of circuits connected), complexity (number of sections, tie-breakers, isolator switches / disconnectors, etc.) and voltage level (transmission, distribution).

The above technical aspects combined with economic factors yield a number of protection solutions.

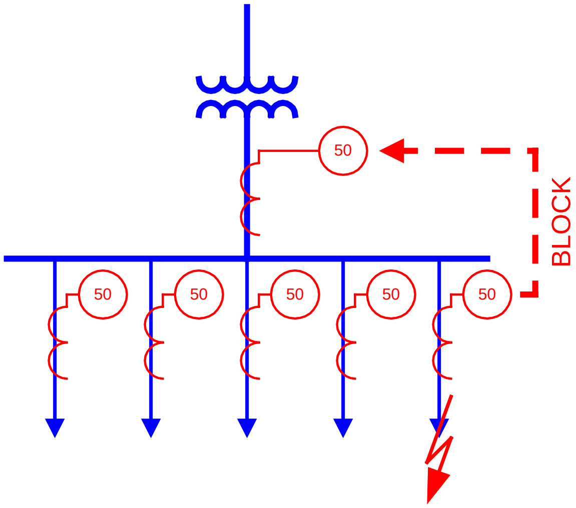

Fig.1. Illustration of the interlocking scheme.

2.1. Interlocking Schemes

A simple protection for distribution busbars can be engineered as an interlocking scheme. OverCurrent (OC) relays are placed on an incoming circuit and at all outgoing feeders. The feeder OCs are set to detect feeder faults. The OC on the incoming circuit is set to trip the busbar unless blocked by any of the feeder OC relays (Figure 1). A short coordination timer is required to avoid race conditions.

When using microprocessor-based multi-function relays it becomes possible to integrate all the required OC functions in one or few relays. This allows not only to reduce the wiring but also to shorten the coordination time and speed-up operation of the scheme.

Modern relays provide for fast peer-to-peer communications using protocols such as the UCA with the GOOSE mechanism. This allows eliminating wiring and sending the blocking signals over digital communications.

The scheme although easy to apply and economical is limited to simple distribution busbars.

2.2. Overcurrent Differential

Typically a differential current is created externally by summation of all the circuit currents and supplied to an overcurrent relay (Figure 2). Preferably the CTs should be of the same ratio. If not, matching CTs are required. This in turn may increase the burden for the main CTs and make the saturation problem even more significant.

Historically, means to deal with the issue of CT saturation include definite time or inverse-time overcurrent characteristics.

Although economical and applicable to distribution busbars, this solution does not match performance of more advanced schemes and should not be applied to transmission-level busbars.

The principle, however, may be available as a protection function in an integrated microprocessor-based busbar relay. If this is the case, such unrestrained differential element should be set above the maximum spurious differential current and may give a chance to speed up operation during heavy internal faults.

2.3. Percent Differential

Percent differential relays create a restraining signal in addition to the differential signal and apply a percent (restrained) characteristic. The choices of the restraining signal include “sum”, “average” and “maximum” of the bus currents. The choices of the characteristic include typically single-slope and double-slope characteristics.

This low-impedance approach does not require dedicated CTs, can tolerate substantial CT saturation and provides for comparatively high-speed tripping.

Many integrated relays perform CT ratio compensation eliminating the need for matching CTs.

This principle became attractive with the advent of microprocessor-based relays because of the following:

- Advanced algorithms supplement the percent differential protection function making the relay very secure.
- Protection of re-configurable busbars becomes easier as the dynamic bus rep-

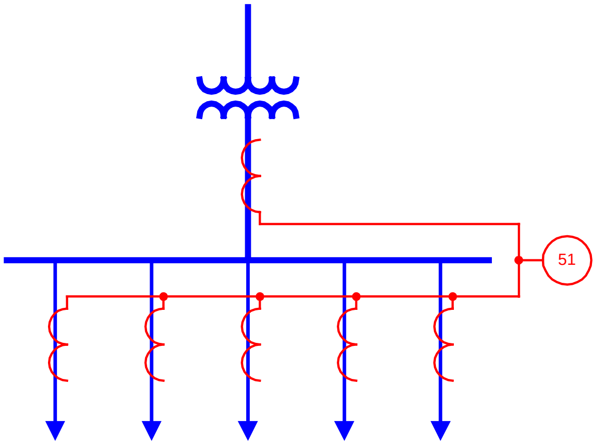

Fig.2. Unrestrained differential protection.

lica (bus image) can be accomplished without switching secondary currents.

- Integrated Breaker Fail (BF) function can provide for optimum tripping strategy depending on the actual configuration of a busbar.
- Distributed architectures could be used that place Data Acquisition Units (DAU) in bays and replace current wires by fiber optic communications.

2.4. High-Impedance Protection

High-impedance protection responds to a voltage across the differential junction points. The CTs are required to be of a low leakage (completely distributed windings or toroidal coils). During external faults, even with severe saturation of some of the CTs, the voltage does not rise above certain level, because the other CTs will provide a lower-impedance path as compared with the relay input impedance. The principle has been used for more than half a century because is robust, secure and fast.

The technique, however, is not free from disadvantages. The most important ones are:

- The high-impedance approach requires dedicated CTs (significant cost associated).
- It cannot be easily applied to re-configurable busbars (switching currents with bi-stable auxiliary relays endangers the CTs, jeopardizes security and adds an extra cost).
- The scheme requires only a simple voltage level sensor. If BF, event recording, oscillography, communications, and other benefits of microprocessor-based relaying are of interest, then extra equipment is needed (such as a Digital Fault Recorder or dedicated BF relays).

2.5. Protection using Linear Couplers

A linear coupler (air core mutual reactor) produces its output voltage proportional to the derivative of the input current. Because they are using air cores, linear couplers do not saturate.

During internal faults the sum of the busbar currents, and thus their derivatives, is zero. Based on that, a simple busbar protection is achieved by connecting the secondary windings of the linear couplers in series (in order to respond to the sum of the primary currents) and putting a voltage sensor to close the loop (Figure 3).

Disadvantages of this approach are similar to those of the high-impedance scheme.

2.6. Microprocessor-based Relays

The low-impedance approach used to be perceived as less secure when compared with the high-impedance protection. This is no longer true as microprocessor-based relays apply sophisticated algorithms to match the performance of the high-impedance schemes [1-6]. This is particularly relevant for large, extra high voltage busbars (cost of extra CTs) and complex busbars (dynamic bus

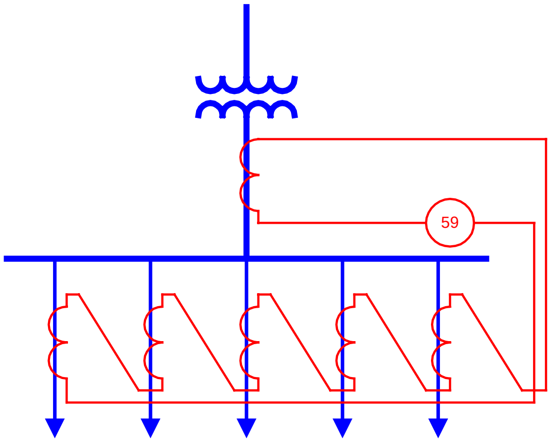

Fig.3. Busbar protection with linear couplers.

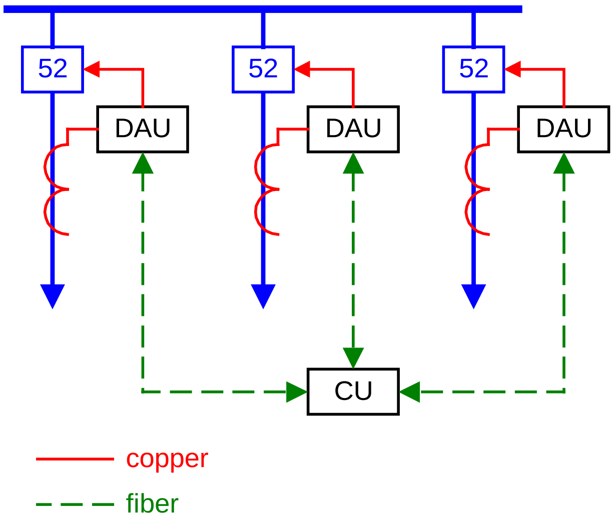

Fig.4. Distributed busbar protection.

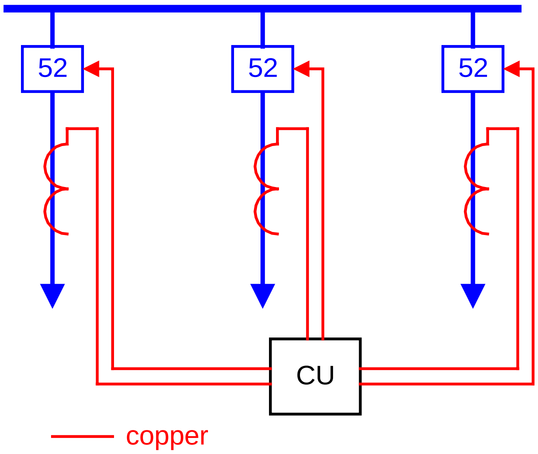

Fig.5. Centralized busbar protection.

replica) that cannot be handled well by high-impedance schemes.

Digital low-impedance relays could be developed in one of the two distinctive architectures:

- Distributed busbar protection uses DAUs installed in each bay to sample and pre-process the signals and provide trip rated output contacts (Figure 4). It uses a separate Central Unit (CU) for gathering and processing all the information and fiber-optic communications between the CU and DAUs to deliver the data. Sampling synchronization and/or time-stamping mechanisms are required. This solution brings advantages of reduced wiring at the price of more complex, thus less reliable, architecture.
- Centralized busbar protection requires wiring all the signals to a central location, where a single "relay" performs all the functions (Figure 5). The wiring cannot be reduced and the calculations cannot be distributed between plurality of DAUs imposing more computational demand for the central unit. On the other hand, this architecture is perceived more reliable and suits better retrofit applications.

Algorithms for low-impedance relays are aimed at [8]:

(a) Improving the main differential algorithm by providing better filtering, faster response, better restraining technique, robust switch-off transient blocking, etc.

(b) Incorporating a saturation detection mechanism that would recognize CT saturation on external faults in a fast and reliable manner.

(c) Applying a second protection principle such as phase directional (phase comparison) for better security.

Digital relays for large busbars dominating the market till recently provide for a trip time in the range of 0.75 to 1.5 power cycles, and use either phase comparison principle or decaying restraining current for increased security on external faults. They were designed several years ago based on technology that since then was outdated by several generations of microprocessors.

In the meantime several new busbar relays have been introduced based on modern, more powerful hardware platforms [7,8]. These relays provide for faster tripping time and modern features, but till recently their capabilities were limited to small (typically six-circuit) busbars.

This changed with the introduction of digital, phase-segregated, low-impedance protection schemes.

3. Phase-Segregated Busbar Relays

The problem of large number of inputs and outputs required for protection of medium-size and large busbars, as well as computational power required to perform all the necessary operations on the inputs, could be solved by using phase segregated approach to busbar protection.

From the perspective of the main differential protection, the 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 several important consequences and advantages.

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 devices.

Second, sampling synchronization is not required between the separate devices processing signals that belong to individual phases.

The above observations facilitate phase segregated busbar protection. With reference to Figure 6, three separate relays (Intelligent Electronic Devices, IEDs) could be used to set up protection for a three-phase busbar. Each device is fed with AC signals belonging to the same phase, processes these signals, and arrives at the trip/no-trip decision. On solidly grounded systems, at least one device would operate for any type of fault. For phase-to-phase faults, two relays would operate.

In order to protect a medium-size busbar it is enough that each IED supports some 18-24 AC inputs. Present protection platforms support this amount of AC inputs. A modern multi-winding transformer, or small busbar relay, could thus be converted from a three-phase device into a single-phase differential device. Instead of supporting four or more three-phase inputs, and some ground inputs, the relay supports 18-24 generic AC inputs and allows for configuring them as inputs to the same zone of differential protection.

This approach yields a number of significant benefits. The three most important ones are: First, by building on existing platforms, the vendors could develop such a solution in a short time with a very low investment. Second, utilizing standard platforms brings extra maturity and features into the busbar applications. Third, by building on standard hardware platforms, the manufacturing cost is also reduced. Consequently, the overall cost of the phase-segregated solution is substantially lower as compared with traditional, “specialized” digital busbar relays. Other features, benefits and peculiarities of the phase-segregated approach are discussed in subsection 3.6.

Busbar protection is more then a plain differential function. The following subsections address several issues related to features such as breaker failure protection, undervoltage supervision, dynamic bus replica, etc.

3.1. Differential Protection

The main differential protection function is implemented on a per-phase basis. A given solution could be more flexible, cost-efficient, and allowing more demanding applications, if multiple zones of protection are available.

A full-featured digital busbar protection system incorporates dynamic bus replica function. This includes both ability to dynamically assign currents to the relay differential zones, and provide for reliable monitoring of the status signals for isolator switches and breakers. The latter is typically implemented by utilizing both normally open and normally closed auxiliary switches as explained in subsection 3.4.

Undervoltage supervision (release) of the main differential function is an often-used feature. This feature guards the system against CT trouble conditions and problems with the dynamic bus replica (false position of a switch/breaker). Typically, phase undervoltage, or neutral and/or negative-sequence overvoltage functions are used. The phase-segregated approach treats single-phase voltage inputs in a generic way. The user could wire phase voltages or neutral (broken delta VT) voltages for the purpose of voltage supervision to all, or selected IEDs only. As a rule, a voltage abnormality in any phase releases all three phases of differential protection. This calls for simple inter-IED communications. This could be done via input contacts, or digital inter-IED communications means.

In the phase-segregated approach each phase IED could drive an output contact for the trip command. This could be done on a per-breaker basis, if required. External lockout relays may be used to gather the per-phase trip commands in order to generate a single three-pole trip signal, if required.

3.2. Inter-relay Digital Communications

Eliminating the AC data traffic between the devices facilitates the digital phase-segregated busbar protection scheme. It is very beneficial, however, to provide for fast, reliable, fully programmable communications mean for sharing on/off states between the IEDs comprising the busbar protection system. Important applications of such a communications mean are as follows:

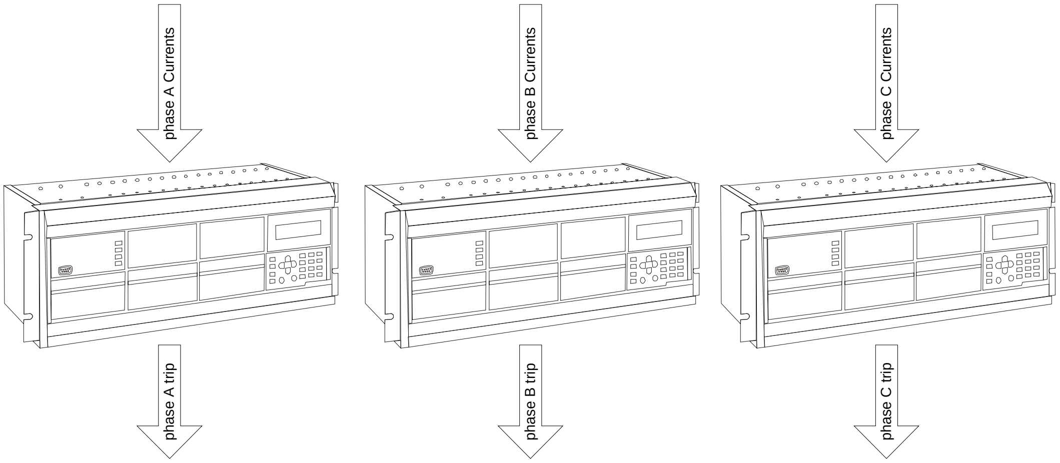

Fig. 6. Phase-segregated digital busbar scheme.

- A large number of I/O points could be freely distributed between the devices. This means that the same information that is common for all three-phases, such as position of a motorized switch, could be wired just to one IED, and distributed to the remaining IEDs via digital communications.
- Applications such as cross triggering of oscillography, undervoltage supervision, check-zone could be easily accomplished by sharing on/off signals via communications channels.
- Certain breaker failure architectures rely heavily on digital communications as explained in subsection 3.3.
- Certain dynamic bus replica solutions rely on communications as well. Tens or hundreds of digital inputs required for monitoring all the switches and breakers, could be wired to an extra relay (relays), where basic filtering (contact discrepancy and alarming) is performed, and the final status signals for the differential protection is sent via communications (subsection 3.4).

One particular solution [9] uses redundant token-ring-like communications mechanism as shown in Figure 7. Up to eight devices could be connected. Each device could share up to 96 points with all the other devices. The mechanism is based on the “auto-forwarding”: each message is received, decoded if required, and forwarded to the next device. When the originating device receives its own message back, it stops forwarding it. This is also a sign that the communications ring is healthy. Two rings increase reliability and reduce (by half) the maximum message delivery time. Available physical media include fiber, RS422 and G.703. As the devices are connected directly, the 820 nm fiber connection is typically used. 32-bit CRC is implemented for security, and the messages are repeated for extra dependability. The maximum delivery time between two neighboring devices is 2-3 msec. Broken-ring alarm is incorporated for overall reliability of the scheme. Default states are available in order to program response of the scheme should the communications fail.

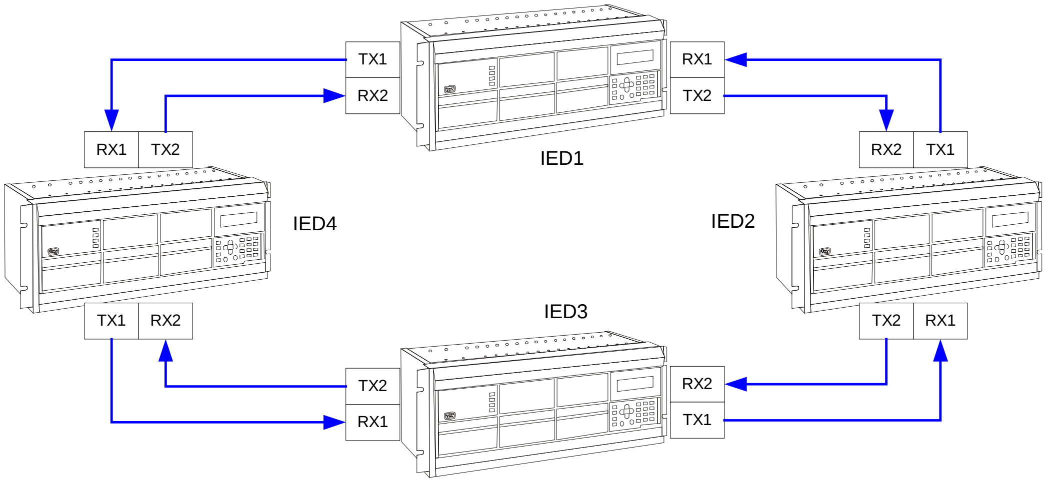

Fig. 7. Inter-IED communications for sharing on/off signals.

3.3. Breaker Failure Protection

Integrated Breaker Failure (BF) protection is quite beneficial for complex busbars. The BF system must monitor configuration of a busbar at any given time, in order to initiate appropriate trip action upon a failure of a given breaker. Basically, this information is identical with the information required by the main differential protection. Doubling this information, i.e. using two separate systems for differential protection and breaker failure, is not economical as a very significant number of I/O points is required to interface the scheme with auxiliary switches of all the isolator switches and breakers. This leads towards integration of the busbar and breaker failure protection functions.

The BF imposes a design challenge for phase-segregated approaches. Large number of currents must be monitored, large number of I/O points must be monitored or driven, and large computational power is required to process those signals.

One particular solution monitors the currents using the phase IEDs and sending the corresponding pickup / dropout signal via digital communications. This means that the devices wired to a given signal is responsible for monitoring the level of the signal and informing the BF-dedicated IED regarding the level of the current.

With reference to Figure 8, devices 1, 2 and 3 are main protection devices for phases A, B and C, respectively; while device 4 is a BF-dedicated device. Devices 1, 2, and 3 feed constantly the fourth device with information regarding the current level. This does not create any extra bandwidth requirements as only changes of the states initiate transmission. Device 4 hosts all the BF schemes for all the breakers. Typically this device is configured to interface all the required I/O points. The BF functions could be initiated externally (typically via contact input), or internally (typically via communications). If any of the BF functions times out and operates, it closes an output contact on device 4, or sends a signal via communications to close any dedicated contact located on any of the remaining devices of the scheme.

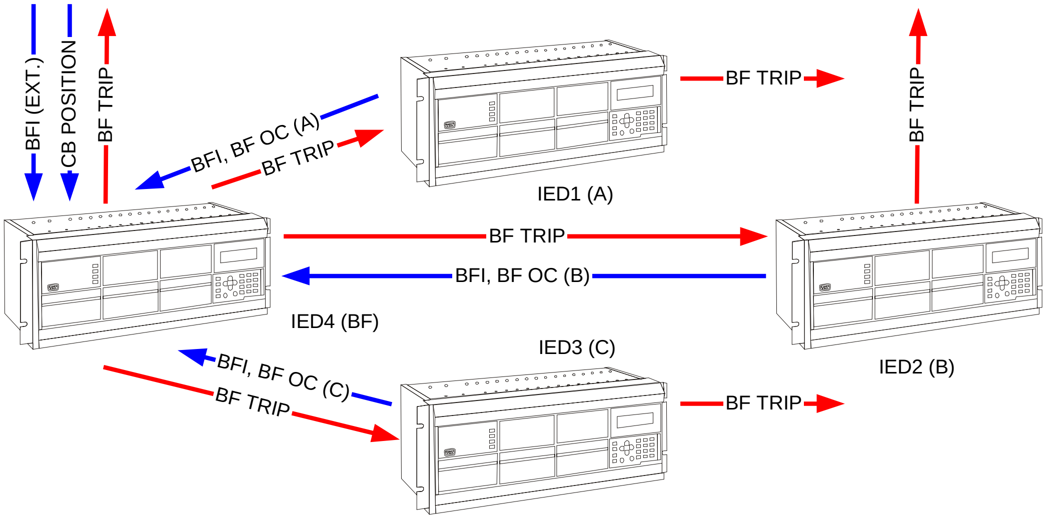

Fig. 8. Sample Breaker Failure Solution.

For simple busbars external BF relays could be used. When the busbar is re-configurable, however, it is always beneficial to have the BF function integrated with the dynamic bus replica function of the main differential protection.

3.4. Dynamic Bus Replica

Dynamic bus replica feature is critical for re-configurable and complex busbars. An actual bus image must be monitor by the protection system for the following purposes.

First, for circuits with a single CT point that could be routed between different sections of the busbar, position of the isolator switch must be known in order to dynamically decide if the CT current belongs to a given zone of protection.

Second, for circuits with a single CB point that could be routed between different sections of the busbar, position of the isolator switch must be known in order to dynamically decide if the CB should be tripped upon operation of a given zone of protection.

Third, the BF protection should monitor all the breakers connected to a given breaker, in order to decide a tripping strategy should the said breaker fail.

Fourth, positions of breakers and tie-breakers should be monitored in order to avoid blind spots or over-tripping zones.

Fifth, certain complex switching strategies call for significant re-adjustments of zone boundaries. The re-adjustment should be programmed as a response to the changing configuration of the busbar.

Section 4 addresses the aforementioned application considerations. Here, the aspect of dynamic zone boundaries, and the isolator monitoring feature are discussed.

Dynamic zone boundary could be programmed using a very straightforward mechanism of configuring a zone of protection as a list of pairs: current input – on/off status signal. A given current becomes a part of the zone only if the corresponding status signal is asserted. Such a mechanism allows for maximum flexibility as the connection status signals could be freely programmed in user-programmable logic of the relay based on a number of conditions, and different protection philosophies.

Auxiliary switches could fail to respond correctly. This is particularly true for motorized switches. Wrong assignment of a given current to a given zone – caused by incorrect information regarding bus configuration – could result in a false trip (typically) or a failure to trip (rarely). Therefore, an isolator monitoring element should respond to both normally open and normally closed auxiliary contacts of an isolator or a tie-breaker in order to assert the actual position of the isolator for the dynamic bus image. Ideally, the element should assert two extra outputs for isolator alarm (contact discrepancy), and for blocking switching operations in the substation.

Traditionally, the following logic is applied.

Table 1. Standard Isolator Monitoring Logic.

Isolator Open Auxiliary Contact	**Isolator Closed Auxiliary Contact**	**Isolator Position**	**Alarm**	**Block Switching Operations**
Off	On	CLOSED	No	No
Off	Off	LAST VALID	After time delay until acknowledged	Until Isolator Position is valid
On	On	CLOSED		
On	Off	OPEN	No	No

Typically, an alarm is set when contact discrepancy is detected. Depending on the type of discrepancy, either the last valid isolator position is assumed, or a “close” position is declared.

It may be beneficial to block switching operations in the substation should a problem with the bus image occur. An operator could remove such blocking signal once the nature of the problem is discovered and rationalized.

3.5. Modularity

Some phase-segregated solutions offer extra modularity at the IED level [9]. This may include variable number of DSPs, and I/O cards as well as communications and redundant power supply. This brings an advantage of shaping each IED of the busbar protection system to fit the needs of a particular application.

With reference to Figure 9b, an IED may be configured with 2 DSPs only, allowing measuring 2 x 8 currents, thus protecting busbars of up to 16 breakers. Figure 9c presents a sample configuration with 3 DSPs (24 AC inputs), 3 I/O modules (up to 3 x 16 inputs, or 3 x 8 outputs) and digital communications card. Figure 9d shows a configuration aimed at interfacing exclusively I/O points, with no DSPs, but 5 I/O modules, communications, and a redundant power supply.

3.6. Sample Protection System Configurations

Phase-segregated protection schemes, particularly the ones providing for extra I/O capabilities, equipped with digital communications means, and supporting multiple zones of protection

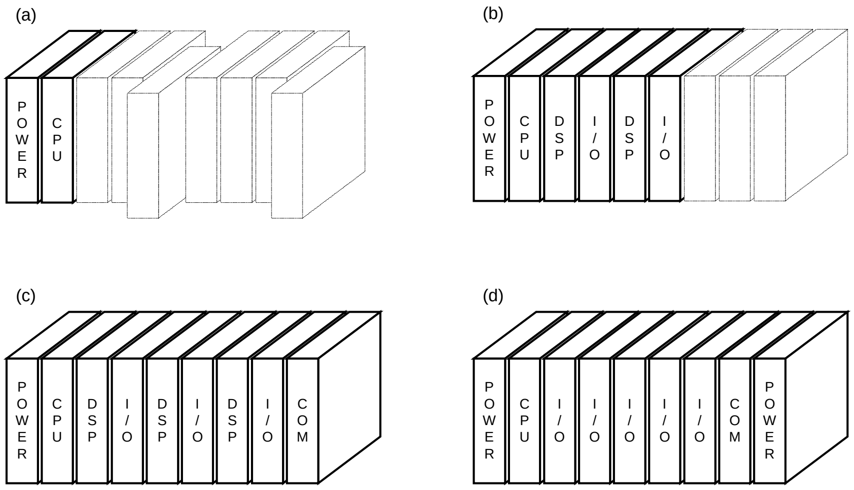

Fig. 9. Sample configurations of a modular system: (a) power supply and CPU are mandatory, (b) 2 DSP, 2 I/O configuration for up to 16 current inputs, (c) 3 DSP, 3 I/O configuration with communications for up to 24 current inputs, (d) 5 I/O configuration with communications and dual power supply.

could be configured to protect a variety of busbar configurations.

Modular hardware platforms such as [7-9] are particularly attractive as they provide for two levels of scalability. First, each IED could be configured to suit the needs of a given application (number of current and voltage inputs, number of digital inputs, number and type of contact outputs, etc.). Second, the scheme could be configured from 1, 2, 3, 4, 5 or even more IEDs depending on complexity of a given application.

Figures 10 through 13 present sample applications.

Figure 10 shows a single-IED protection for a simple eight-input busbar. The 24 current channels available could be wired to 8 three-phase inputs; while 3 single-phase zones of protection could be configured to provide differential protection for phases A, B and C.

A similar solution for busbars of up to 12 inputs could be built on 2 IEDs. The first IED uses 2 zones to protect 12-input busbars in phases A and B. The second IED uses one of its zones and 12 input signals to protect the remaining phase C.

Using multiple protection systems one could cover large busbars as long as each section is of a medium size and a check zone is not required or done externally (Figure 13).

3.7. Advantages and Benefits

The main advantages and benefits of a phase-segregated approach to digital low-impedance busbars protection schemes are as follows.

Because the phase-segregated relays are typically developed based on existing hardware platforms, reusing probably some 90% of existing firmware, they are much more cost-efficient as compared with dedicated schemes for large busbars.

Being built on existing hardware and firmware, with thousands of unit-years of field record, the new solutions are much more mature, and could reach better maturity indices fast, as compared with dedicated schemes installed in very low volumes. This allows reducing a risk of installing a “new” busbar relay – the new relays are actually quite mature as their hardware and

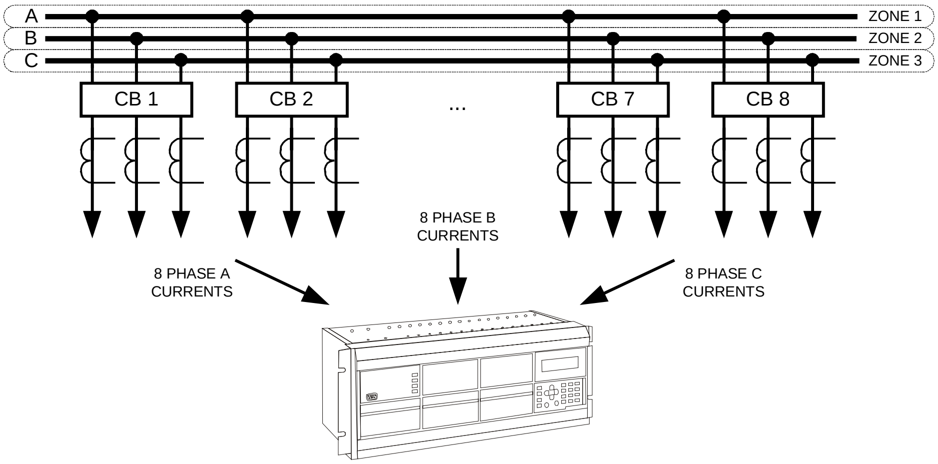

Fig. 10. Three-phase protection for small busbars.

majority of firmware work already as a transformer or small busbar relay in numerous installations.

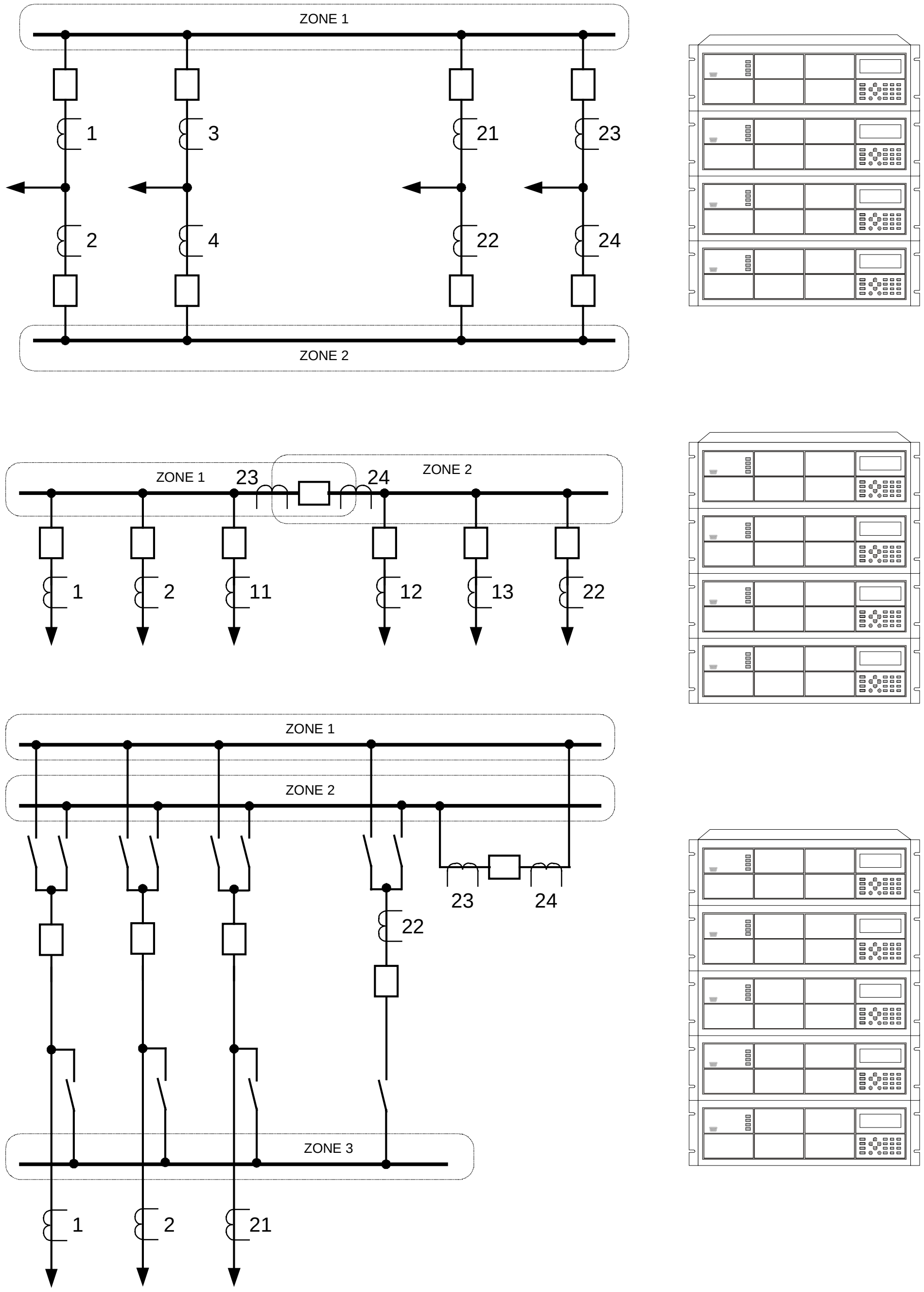

Fig. 11. Sample system configurations: breaker-and-half, two-section busbar with a tie-breaker, double busbar with tie-breaker and a transfer bus.

The new relays have been developed from a simple solution up towards a sophisticated one. In this way the design was not biased towards ability of protecting 50+ circuit busbars. Because of that the configuration mechanisms, associated software and settings are simple and already known to the user from transformer and small busbar applications. The new solutions are easier to engineer as compared with dedicated large-busbar protection systems.

Being built on existing hardware and firmware platforms, the new busbar relays are members of existing relay lines. They share common tools. They could be integrated with other members of the relay line. The overall user learning curve could be significantly reduced.

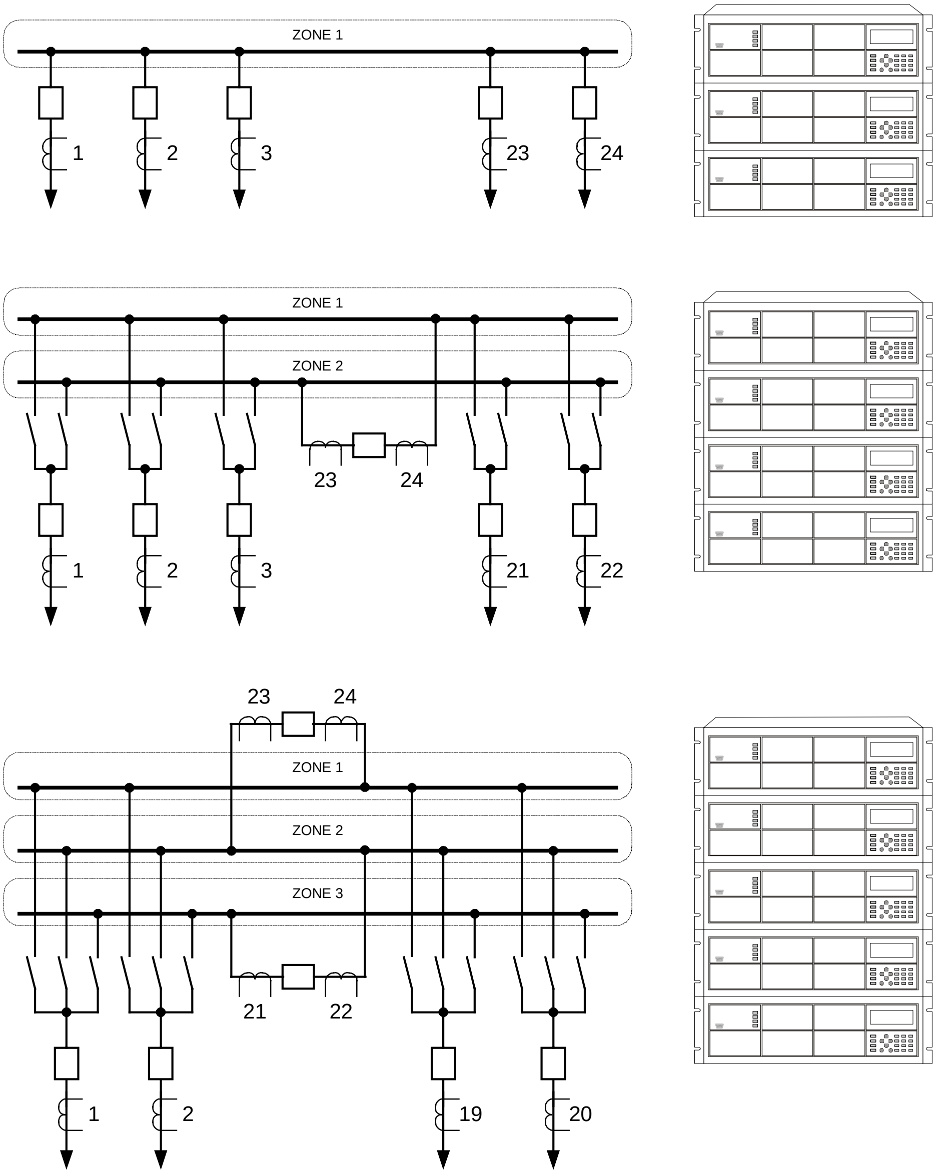

Fig. 12. Sample system configurations: single-, double- and triple busbars.

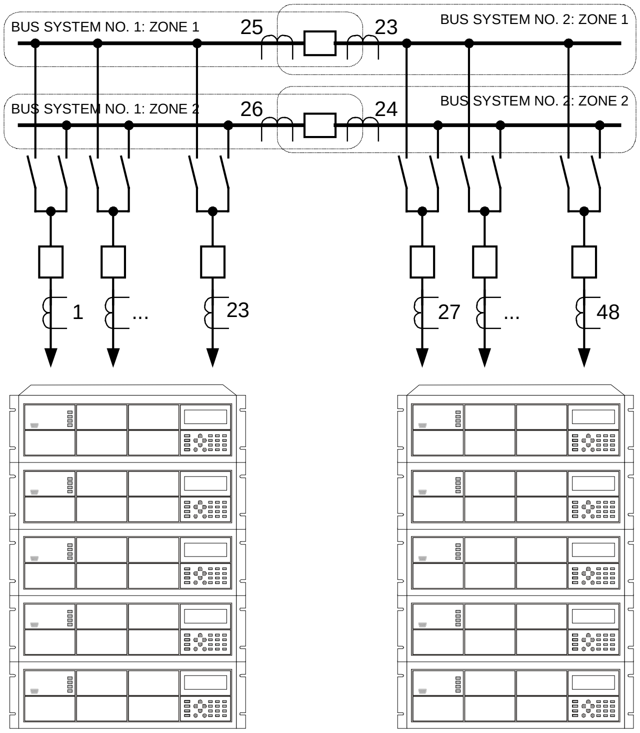

Fig. 13. Sample system configurations: a large busbar protected by two protection systems.

Certain configurations of phase-segregated solutions exhibit enhanced immunity to relay failures. Consider for example, a simple system built on three devices protecting phases A, B and C without any communications. If one of the devices fails, the system is still operational providing protection for all kinds of faults except a SLG fault in the affected phase. Even more complex systems with communications could be programmed so that the main functions remain intact when certain components of the scheme fail.

Oscillography and Sequence of Events recording capabilities are multiplied by using multiple IEDs. Simple software tools exist to "consolidate" SOE records, and comtrade files into single files for easier analysis. Programming the IEDs for cross triggering of various records, and setting up a common clock reference signal (IRIG-B) allows good synchronization of records between the IEDs comprising the busbar protection system.

User-programmable logic is available in each of the IEDs allowing easier engineering and more flexible application as compared with dedicated "hard-coded" schemes that had to be set up by the vendor, rather than the user.

4. Application Considerations

This section presents application considerations with respect to protecting complex busbar arrangements and/or when the objective is to provide for optimum protection by avoiding blind spots or unnecessary bus outages. As a rule, this task calls for dynamic adjustments of boundaries of differential zones of protection, and can be safely accomplished when using numerical relays.

In the following examples it is assumed that the dynamic bus replica feature is implemented by configuring a differential zone using pairs of (current signal, associated connection status signal). A given current is included in the zone, only if the associated status signal is logic one. In this way each current input of the relay could be logically added or removed from the zone, depending on changing busbar configuration.

It is also assumed that the auxiliary logic variables required for bus configuration are programmed in user-programmable logic of the relay.

4.1. Switchable Bus Circuits

Figure 14 presents a sample double busbar arrangement with bus sections 1 and 2, tie-breaker CB-1, three outgoing circuits C-1, C-2 and C-3, and a number of CTs and isolator switches. It is assumed that the two sections could operate independently, with the tie-breaker opened or closed. Each section could be used as a transfer bus.

Several complex configurations are possible in the busbar of Figure 14. They are addressed in the following subsections. However, if none of the isolators S-5 and S-6, S-7 and S-8, and S-9 and S-10 could be closed simultaneously, the two sections could and should be protected independently by two zones of protection. This could be programmed as the following zone configurations.

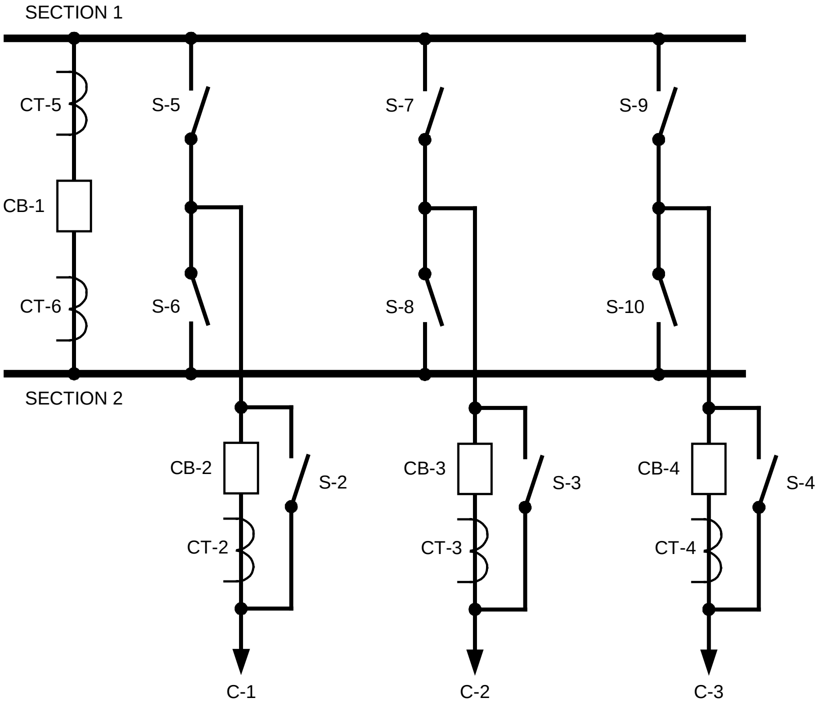

Fig. 14. Sample double-bus arrangement.

Table 2. Sample Zone Configuration for busbar of Figure 14.

ZONE 1			ZONE 2		
Z1 Input 1	Current	CT-6	Z2 Input 1	Current	CT-5
	Status	On		Status	On
Z1 Input 2	Current	CT-2	Z2 Input 2	Current	CT-2
	Status	S-5		Status	S-6
Z1 Input 3	Current	CT-3	Z2 Input 3	Current	CT-3
	Status	S-7		Status	S-8
Z1 Input 4	Current	CT-4	Z2 Input 4	Current	CT-4
	Status	S-9		Status	S-10

The setting of Table 2 are interpreted by the relay as follows: the CT-5 current belongs always to Z1; the CT-2 current belongs to Z1 only if switch S-5 is closed; the CT-3 current belongs to Z1 only if switch S-7 is closed, etc.

Operation of a given zone should be routed to the breakers using bus configuration at the moment of tripping. In this example, the following trip commands should be created:

TRIP CB-1 = Z1 OR Z2 (1)
TRIP CB-2 = (Z1 AND S-5) OR (Z2 AND S-6) (2)
TRIP CB-3 = (Z1 AND S-7) OR (Z2 AND S-8) (3)
TRIP CB-4 = (Z1 AND S-9) OR (Z2 AND S-10) (4)

Where Z1 and Z2 stand for operation of differential zones 1 and 2, respectively.

Breaker Failure protection should force an associated differential zone to operate in order to trip all the breakers currently connected to the failed breaker. For the busbar of Figure 14 this should be programmed as follows:

FORCE Z1 = BF-1 OR (BF-2 AND S-5) OR (BF-3 AND S-7) OR (BF-4 AND S-9) (5)
FORCE Z2 = BF-1 OR (BF-2 AND S-6) OR (BF-3 AND S-8) OR (BF-4 AND S-10) (6)

Assume for example S-5, S-8 and S-9 closed; S-6, S-7 and S-10 opened; and CB-2 failing to trip for a circuit fault. BF-2 would force Z1 to operate (equation (5)). Z1 would trip breakers CB-1 (equation (1)) and CB-4 (equation (4)). This would clear the currents towards CB-2, but would leave section 2 and circuit C-2 in service.

The above example illustrates a classical situation when the dynamic bus replica is required. The application may get more complex if certain switching scenarios are allowed in the substation of Figure 14 (subsection 4.6).

Application of the dynamic bus replica is also beneficial when protecting simple and non-switchable busbars as explained in subsections 4.2, 4.3 and 4.4.

4.2. Line-Side CTs

A differential zone must be terminated by points where a CT is present in order to locate a fault (selectivity) and a CB is present in order to isolate the fault (trip action). Although positioned very closely, the two devices have a finite space between them. This space is potentially exposed to faults. Depending on the mutual position of the CT and CB, the said space may become either a blind spot or may cause unnecessary trip of the busbar.

Consider an arrangement shown in Figure 15. When the CB is opened, the space between the line-side CT and the CB is an over-tripping zone: a fault between the CB and CT is not a bus fault as the breaker is already opened and no current is supplied from the bus towards the fault. From the metering perspective, however, the fault is within the zone. If the current is statically assigned to the zone of protection, an unnecessary trip takes place.

Using breaker position as a connection status for the associated current could easily solve the problem. When the breaker is opened, the current is removed from the zone. As a result the zone boundary moves from the CT point to the bus-side pole of the opened CB. The zone contracts and the unnecessary trip of the busbar is prevented.

The drop out delay applied to the breaker position signal is necessary to allow measuring algorithms of the relay to ramp down after the current is interrupted by the breaker. Otherwise a false trip would take place when the breaker opens.

Refining example of Figure 1, one should take care of the spots between CT-5 and CB-1 (for zone 2) and CT-6 and CB-1 (for zone 1). Consequently, the status signals for CT-5 and CT-6 would be as follows:

Z1 Input 1 Current = CT-6 (7)
Z1 Input 1 Status = CB-1 + drop out delay (8)
Z2 Input 1 Current = CT-5 (9)
Z2 Input 1 Status = CB-1 + drop out delay (10)

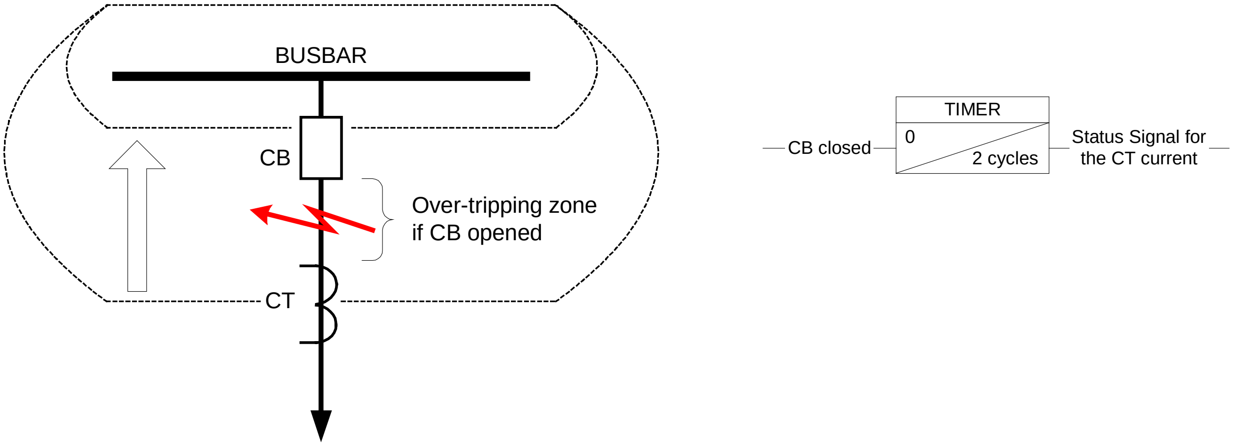

Fig. 15. Line-side CT configuration.

In other words, shortly after CB-1 gets opened, Z1 contracts to the section-1 pole of the opened CB-1, while Z2 contracts to the section-2 pole of the CB-1. In this way Z1 would not respond to faults between CT-6 and CB-1, and Z2 would not respond to faults between CT-5 and CB-1. This is desired for optimum selectivity of protection.

Same approach applies to breakers CB-2, CB-3 and CB-4 in Figure 14.

4.3. Bus-Side CTs

Similar situation occurs for bus-side CTs. Consider an arrangement shown in Figure 16. A fault between the CB and CT is in a blind spot of the bus protection. To clear the fault the busbar must be tripped, but the differential zone would not see this fault.

Similarly to the case of the line-side CT, this situation also requires using breaker position as a connection status for the associated current. The fault is cleared sequentially. First, protection of the circuit – fed from the CT – responds to the fault and opens the breaker. When the breaker opens, the CT current is removed from the differential zone. As a result, the zone expands to the bus-side pole of the opened breaker, the fault becomes internal, and the bus protection clears the busbar.

4.4. Tie-breaker with a Single CT

Ideally two CTs should be used for tie-breakers (see Figure 14). In some situations, however, a single CT is installed as shown in Figure 17.

Two differential zones should be arranged in order to provide for selective protection of sections 1 and 2, respectively. As a result of having a single measuring point, a fault between the tie-breaker and the CT is internal to Z1, but external to Z2. Z1 would trip the tie-breaker, but the fault would not be cleared.

Using position of the tie-breaker for the connection status of the CT current for Z2 solves the problem. After TB opens due to operation of Z1, Z2 expands to the opened breaker, the fault becomes internal to Z2, and Z2 finally clears the fault by tripping section 2 of the busbar.

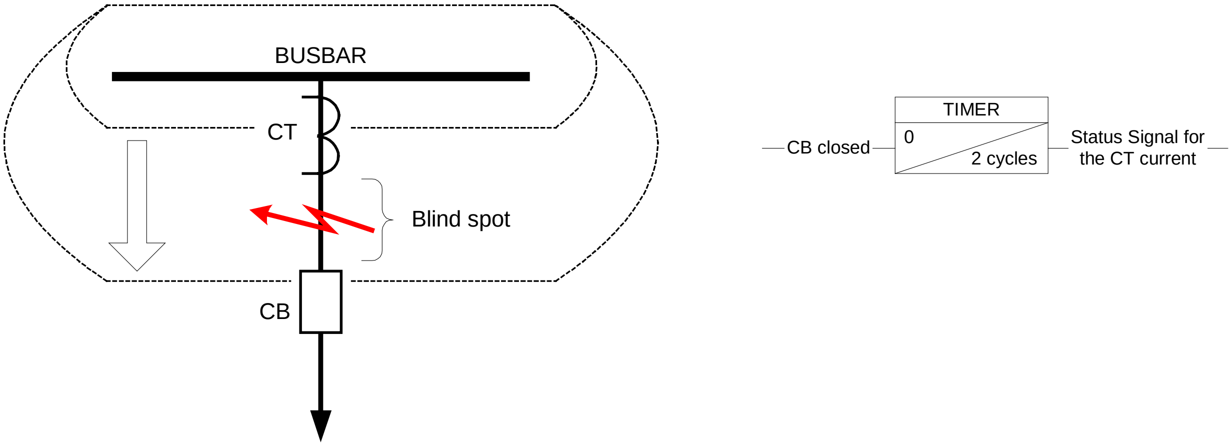

Fig. 16. Bus-side CT configuration.

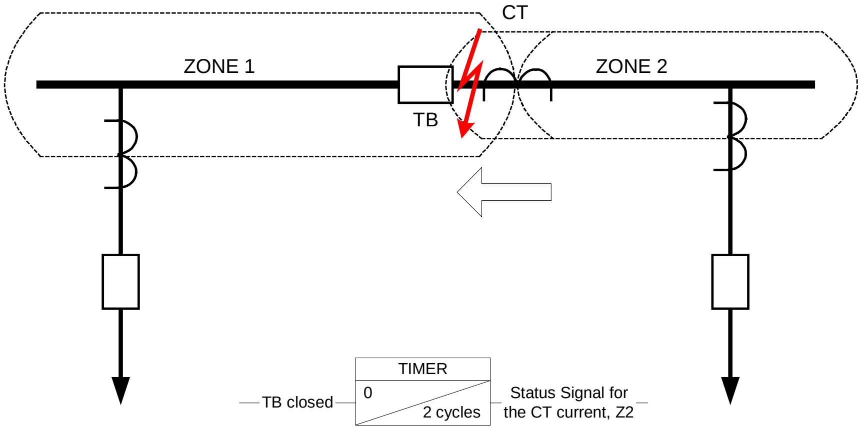

Fig. 17. Tie-breaker with a single CT.

4.5. End Fault Protection

Consider an arrangement of Figure 18. With the CB-1 opened, the bus zone moves from the CT point to the CB-1 point leaving the portion between the CB-1 and CT unprotected.

A simple overcurrent element responding to the CT current and activated when the breaker is opened solves the problem. Such End Fault Protection should trip the CB-2 breaker. If CB-2 is located in the same substation, the application is simple. If CB-2 is located at the remote terminal of a line, Direct Transfer Tripping capability is required. If DTT is not available, CB-2 would be tripped from the backup protection functions at the remote terminal of the line.

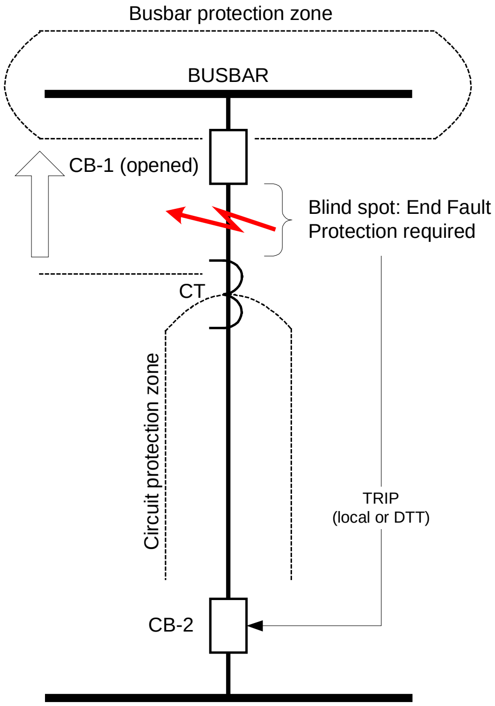

Fig. 18. End Fault Protection.

4.6. Complex Switching Strategies

Complex switching scenarios are often allowed for complex busbar arrangements.

Consider a busbar of Figure 14 and assume a transfer operation that allows closing the two switches (such as S-5 and S-6) simultaneously with the tie-breaker closed prior to the operation. At the moment the two switches are closed, the CT-2 current splits in an unknown proportion between sections 1 and 2. As a result it becomes impossible to protect sections 1 and 2 separately, and the entire busbar must be protected as one entity.

First, such a transfer condition must be detected by the busbar relay. For a busbar of Figure 14, the following auxiliary flag stands for the condition of the two sections connected via switches:

A1 = (S-5 AND S-6) OR (S-7 AND S-8) OR (S-9 AND S-10) (11)

Second, the two zones must be re-arranged so that sections 1 and 2 are protected as one entity. This could be accomplished by one of the following:

- Disable Z1 and expand Z2 accordingly.
- Disable Z2 and expand Z1 accordingly.
- Disable both zones and trip from a check zone (if used).
- Expand both zones to enclose the entire busbar.

The last solution is the most elegant because it is symmetrical. The following table shows zone configurations that account for the transfer scenario.

Table 3. Sample Zone Configuration for busbar of Figure 14 (with transfer capabilities)

ZONE 1			ZONE 2		
Z1 Input 1	Current	CT-6	Z2 Input 1	Current	CT-5
	Status	NOT (A1)		Status	NOT (A1)
Z1 Input 2	Current	CT-2	Z2 Input 2	Current	CT-2
	Status	S-5 OR A1		Status	S-6 OR A1
Z1 Input 3	Current	CT-3	Z2 Input 3	Current	CT-3
	Status	S-7 OR A1		Status	S-8 OR A1
Z1 Input 4	Current	CT-4	Z2 Input 4	Current	CT-4
	Status	S-9 OR A1		Status	S-10 OR A1

Assume for example S-5, S-7 and S-10 closed, and S-6, S-8 and S-9 opened. Under this condition, the zones are dynamically adjusted as follows:

Z1: (CT-6, CT-2, CT-3) (12)

Z2: (CT-5, CT-4) (13)

When subsequently, an action is initiated to transfer circuit C-1 from section 1 to section 2, switch S-6 is closed. As a result of S-5 and S-6 closed simultaneously, variable A1 is asserted (equation (11)). Consequently the zones are re-adjusted as follows (Table 3):

Z1: (CT-2, CT-3, CT-4) (14)

Z2: (CT-2, CT-3, CT-4) (15)

In other words, both zones protect the entire bus. If a fault occurs under this configuration, all the breakers will be tripped. This may include the tie-breaker (not necessary from the fault clearance perspective, but beneficial from the subsequent restoration perspective).

When subsequently S-5 gets opened in order to complete the transfer, A1 resets, and the zones re-adjust again as per Table 3:

Z1: (CT-6, CT-3) (16)

Z2: (CT-5, CT-2, CT-4) (17)

In this way CT-2 (circuit C-2) got transferred between protection zones 1 and 2.

Another operating mode is to transfer all the circuits to one section, say section 1, keep one circuit on the other section (say number 2) in order to service the breaker. Once the by-passing switch is closed, the current of the paralleled CT must be ignored. The bus section connected to the circuit in question becomes part of the circuit and is protected by the circuit relay. In order to accomplish that protection of the circuit must be transferred to the tie-breaker CT as illustrated in Figure 19.

At the same time bus zone that has the non-valid current assigned to it, must be blocked or otherwise it would misoperate. For the busbar of Figure 19 the following auxiliary flags could accomplish this:

A2 = (S-2 AND S-5) OR (S-3 AND S-7) OR (S-4 AND S-9) (18)

A3 = (S-2 AND S-6) OR (S-3 AND S-8) OR (S-4 AND S-10) (19)

Flag A2 means Z1 is fed with at least one invalid current and thus it should be blocked. Flag A3 means Z2 is fed with at least one invalid current and thus it should be blocked. Consider configuration of Figure 19: A2 = 0 (Z1 is not blocked – equation (18)), A3 = 1 (Z2 is blocked– equation (19)).

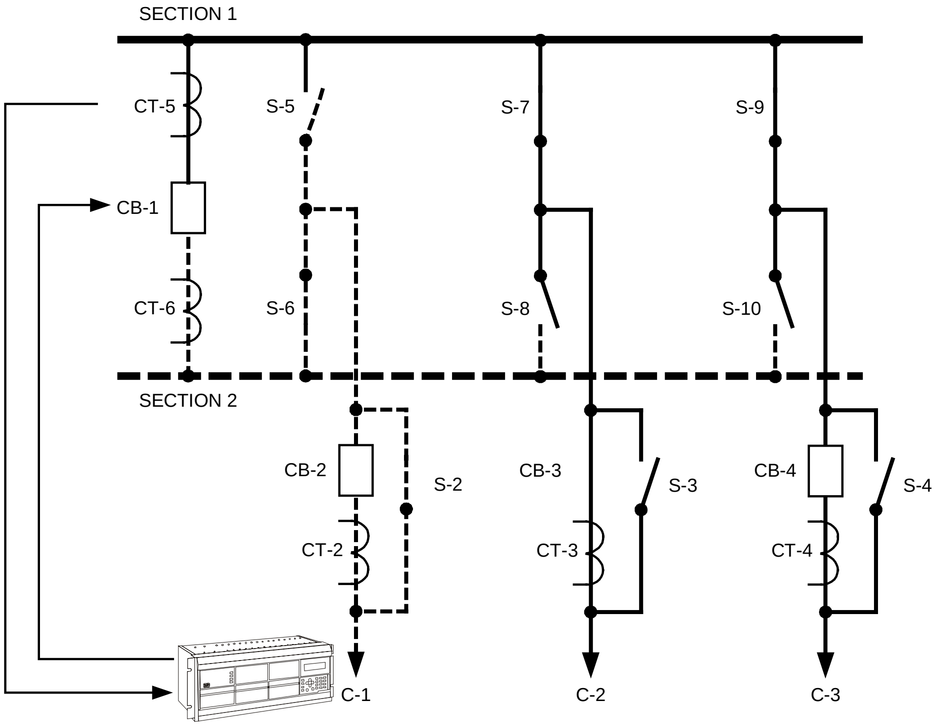

Fig. 19. Bus configuration that allows servicing CB-2.

In this way:

- Z1 is reconfigured to protect section 1 by monitoring the following currents (CT-6, CT-3, CT-4).
- Z2 is blocked and would not misoperate.
- Section 2 is protected by protection of C-1 transferred to CT-5.

4.7. Check Zone

Check zone is a mean of achieving extra security. A check zone is used as a supervising element for regular zones of protection and mitigates problems of wrong status information (incorrect switch or breaker position recognized by the relay). It will also – at least partially – mitigate CT trouble conditions.

The check zone is programmed to monitor the overall current balance for the entire busbar. In the example of Figure 14 the check zone is configured as follows:

Table 4. Check Zone Configuration for busbar of Figure 14.

ZONE 3 (CHECK ZONE)		
Z3 Input 1	Current	CT-2
	Status	On
Z3 Input 2	Current	CT-3
	Status	On
Z3 Input 3	Current	CT-4
	Status	On

Ideally, Z3 should be fed from different cores of the CTs.

There are circumstances when the check zone will not work. Consider configuration of Figure 19. Because the CT-2 current is not valid (due to the S-2 switch closed), it is impossible to check the current balance for the entire busbar. In order to ensure that Z1 would trip for internal faults, the Z3 supervision should by dynamically removed under the circumstances. This could be implemented using the following logic:

$$\text{Z1 SUPVERVISION} = \text{Z3 OR A2} \qquad (20)$$

$$\text{Z2 SUPVERVISION} = \text{Z3 OR A3} \qquad (21)$$

As shown in this section, there are numerous situations when the boundaries of differential zones of busbar protection should be dynamically and automatically re-adjusted. Such operation is natural, easy to program, and safe when using digital low-impedance relays.

5. Summary

Several new phase-segregated low-impedance digital protection schemes for medium and large busbars emerged in 2001 and 2002. Built on existing hardware and firmware platforms these solutions bring in low-cost, initial maturity and simplicity of application.

At the same time existing busbars are being upgraded to accommodate new generation and new power equipment. New substations are built as double-busbars or even more complex arrangements. In new substation designs driven more by cost and less by engineering considerations, motorized switches replace breakers. Sophisticated switching strategies are allowed to cope with various operational conditions. All this creates major problems for high-impedance, or non-digital in general, busbar relays.

A digital busbar protection scheme is a natural choice for protecting such complex re-configurable busbars. Digital relays already reached security of high-impedance schemes [9]. Modern relays provide for a sub-cycle tripping time [9]. With the new phase-segregated approach, the digital schemes become also affordable and easy to engineer, opening new application opportunities.

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