GER-4002

An Innovative Low-Impedance Bus Differential Relay: Principles and Applications

INNOVATIVE DIGITAL LOW IMPEDANCE BUS DIFFERENTIAL RELAY: PRINCIPLES and APPLICATIONS

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ABSTRACT

Power system busbars are electrical nodes that interconnect several circuits such as transmission lines, transformers and generators. Although the probability of a busbar fault is much lower than for other items of a power system, when it occurs it produces serious consequences for the whole electrical network. High-speed selective bus protection can do much towards limiting the effects of a busbar fault on the system.

An innovative microprocessor based busbar differential relay that offers fast and sensitive operation under internal fault conditions and ensures improved stability during external faults is presented. The relay is low impedance with a biased differential characteristic and includes means to detect CT saturation.

The relay includes 2 separate bus differential zones to cover different bus sections using a dynamic bus replica mechanism that allows for protecting buses with circuits inter-connectable between various sections.

1. INTRODUCTION

Busbars are connected to a number of energy sources that all together produce very large fault currents in the event of a short circuit on the bus. On one hand, the failure of the protection to clear an internal bus fault can cause extensive damages and disrupt power system stability. On the other hand, it is equally harmful for a busbar protection to mal operate, because an important node is then removed from the network which can also upset the operation of the entire power system.

In extensive networks a secure and dependable high-speed bus protection is an essential element to maintain stability and, in the vicinity of large generating units can be instrumental in avoiding shaft damages.

The relay presented here is a high-speed low-impedance microprocessor-based current differential relay for power system busbars. The relay includes two separate bus differential zones to cover different bus sections and initiate selective tripping actions. The relay incorporates a dynamic bus replica mechanism that allows for protecting buses with circuits inter-connectable between various sections but with single current measurement points.

As explained in the Theory of Operation section, the relay uses a dual-slope dual-breakpoint differential characteristic with the restraint signal created as the maximum among the magnitudes of the circuit connected to the protected bus. The low-impedance operating principle is enhanced by the use of the Saturation Detector and a current directional principle.

2. THEORY OF OPERATION

Referring to Figure 1, input currents defining – through the dynamic bus replica – the bus differential zone, are received by the relay from Current Transformers (CT's) associated with the power system.

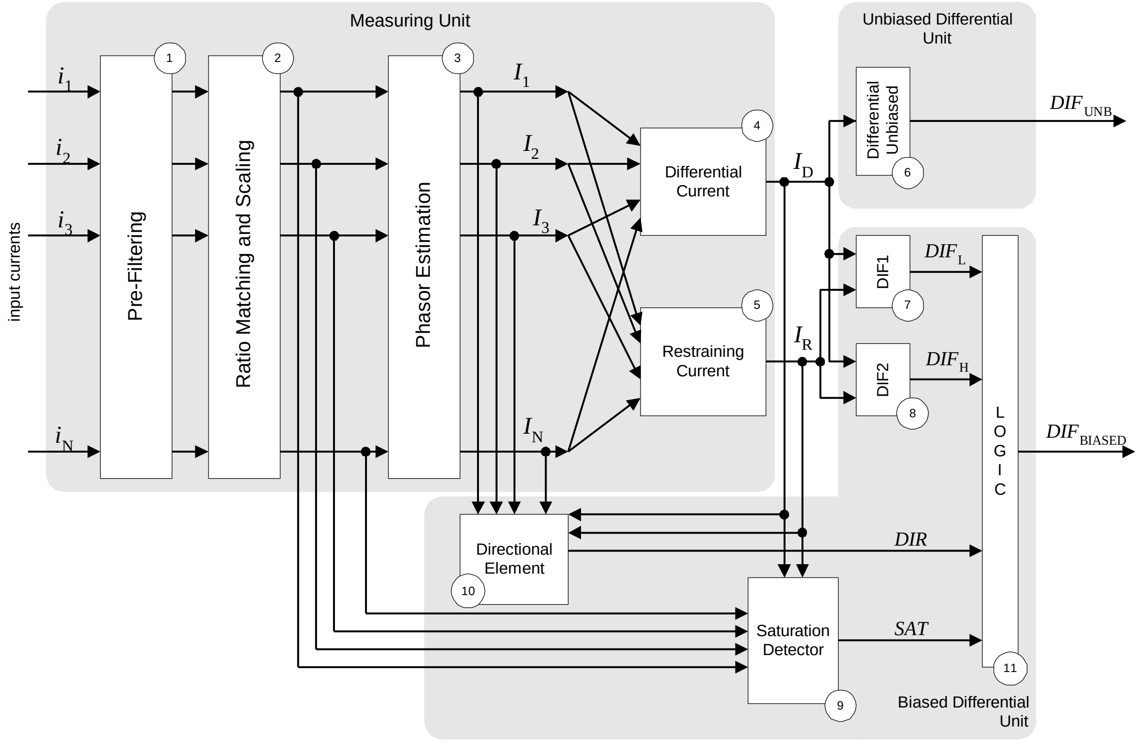


FIGURE 1: OVERALL BLOCK DIAGRAM OF THE BUS DIFFERENTIAL PROTECTION

The currents are digitally pre-filtered (block 1) in order to remove the decaying dc components and other signal distortions.

The filtered input signals are brought to a common scale taking into account the transformation ratios of the connected CT's (block 2, see paragraph 3.2).

Phasors of the differential zone currents are estimated digitally (block 3) and the differential (block 4) and restraining (block 5) signals are calculated (paragraph 4).

The magnitude of the differential signal is compared with a threshold and an appropriate flag indicating operation of the unbiased bus differential protection is produced (block 6). The unsupervised unbiased current differential element operates whenever the measured differential current is above the set value.

The magnitudes of the differential and restraining currents are compared and two auxiliary flags that correspond to two specifically shaped portions of the differential operating characteristic (DIF1 and DIF2) are produced (blocks 7 and 8). The characteristic is split in order to enhance performance of the relay by applying diverse security measures for each of the regions (paragraph 4.3).

The directional element (block 10, paragraph 6) supervises the biased differential characteristic when necessary. The current directional comparison principle is used that processes phasors of all the input currents as well as the differential and restraining currents.

The saturation detector (block 9, paragraph 7) analyzes the differential and restraining currents as well as the samples of the input currents. This block sets its output flag upon detecting CT saturation.

The output logic (block 11, paragraph 8) combines the differential, directional and saturation flags into the unbiased differential operation flag. The applied logic enhances performance of the relay while keeping an excellent balance between dependability/speed and security.

3. DYNAMIC BUS REPLICA AND RATIO MATCHING

3.1. DYNAMIC BUS REPLICA MACHANISM

The relay provides protection for up to two bus differential zones. The bus differential zone of the relay allows for protecting bus sections that include circuits that are switchable between different bus sections. Proper relay operation is achieved by associating a status signal with each input current. This mechanism is referred to as a dynamic bus replica.

The dynamic bus zone is programmed as a number of source – status pairs. The Sources feature of the relay is a convenient and flexible mechanism for associating input currents and voltages with protection and control elements. Normally, each source defining the input to the relay's bus differential zone should be associated with a single physical current transformer bank. (The only situation when two or more currents may be summed up into a single source before entering into the bus zone is when the currents are purely load currents and cannot produce any fault current in any circumstances).

The status signal of a given source – status pair of the dynamic bus replica, is a FlexLogic^{TM} operand created to indicate whether or not the associated circuit (current) is connected to the protected bus zone. Normally, the status signals are to be created from input contacts wired to appropriate auxiliary contacts of switches and/or breakers.

Figure 2 shows an example of a circuit that could be connected to two separate bus sections. It is assumed that each section is protected individually by two different bus zones of a relay (or by two relays). The current signals are brought into the relay using a CT bank, say F1, and assigned to a source, say SRC 1. The status signals of the switches are brought into the relay as input contacts, say H7a and H8b. The input contacts can be used directly (say, Cont Ip 1 On, Cont Ip 2 On), or further processed using the FlexLogic$^{\text{TM}}$ for contact discrepancy filtering or extra security. The pair “SRC 1 – Cont Ip 1 On” defines the input to the BUS ZONE 1, the pair “SRC 1 – Cont Ip 2 On” defines the input to the BUS ZONE 2.

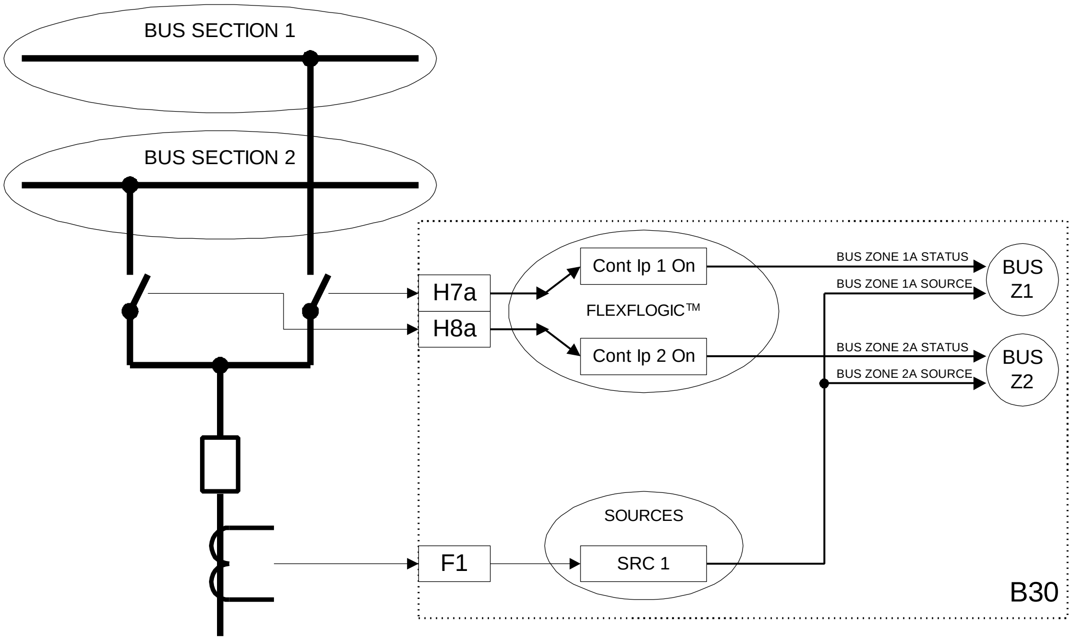


FIGURE 2: ILLUSTRATION OF THE DYNAMIC BUS REPLICA MECHANISM

If a given circuit cannot be connected to any power system element other than the protected bus, then its status signal could be fixed using the FlexLogic$^{\text{TM}}$ “On” constant.

3.2 CT RATIO MATCHING

The relay allows for using CT’s with various rated secondary currents and transformation ratios. Scaling to a common base is performed internally by the relay. The maximum allowable ratio mismatch is 32:1. For proper setting of the differential characteristic it is important to understand the common base used by the relay.

The relay scales the secondary currents to the largest primary current among the CT’s defining a given bus differential zone; this is, 1 per unit corresponds to the highest rated primary current.

The scaling base is selected automatically by the relay during the configuration phase and is not affected by the dynamic aspect of the bus differential zone. This means that even though the circuit containing the CT with the maximum rated primary current is not connected to a given bus zone at a given time, the scaling base does not change.

4. DIFFERENTIAL PRINCIPLE

4.1 BIASED DIFFERENTIAL CHARACTERISTIC

The relay uses a two-slope two-breakpoint operating characteristic shown in Figure 3.

The PICKUP setting is provided to cope with spurious differential signals when the bus carries a light load and there is not any effective restraining signal.

The first breakpoint (LOW BPNT) is provided to specify the limit of guaranteed linear operation of the CT's in the most unfavorable conditions such as high residual magnetism left in the magnetic cores or multiple autoreclosure shots. This point defines the upper limit for the application of the first, lower slope (LOW SLOPE).

The second breakpoint (HIGH BPNT) is provided to specify the limits of operation of the CT's without any substantial saturation. The limit of linear operation that neglects both the residual magnetism and the effect of the dc component, for the CT that is expected to saturate first, should be the base for setting the higher breakpoint of the biased differential characteristic. This point defines the lower limit for the application of the second slope (HIGH SLOPE).

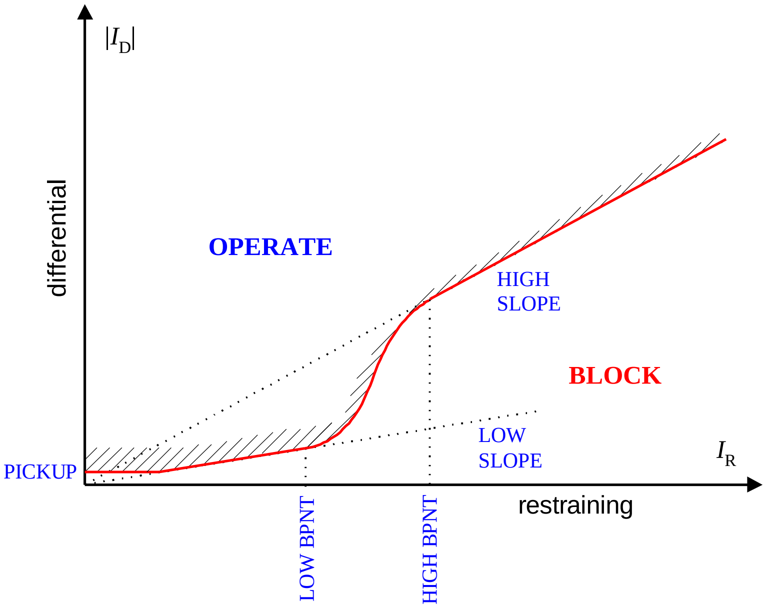


FIGURE 3: BIASED OPERATING CHARACTERISTIC

The higher slope used by the relay acts as an actual percentage bias regardless of the value of the restraining signal. This is so because the boundary of the operating characteristic in the higher slope region is a straight line intersecting the origin of the differential – restraining plane. The advantage of having a constant bias specified by the HIGH SLOPE setting creates an obstacle of a discontinuity between the first and second slopes. This is overcome by using a smooth spline approximation of the characteristic between the lower and higher breakpoints. Consequently, the characteristic ensures:

- a constant percentage bias of LOW SLOPE for restraining currents below the lower breakpoint of LOW BPNT;

- a constant percentage bias of HIGH SLOPE for restraining currents above the higher breakpoint of HIGH BPNT; and
- a smooth transition from the bias of LOW SLOPE to HIGH SLOPE between the breakpoints.

4.2 DIFFERENTIAL AND RESTRAINING CURRENTS

The differential current is produced as a sum of the phasors of the input currents of a differential bus zone taking into account the status signals of the currents, i.e. applying the dynamic bus replica of the protected zone.

The restraining current is produced as a maximum of the magnitudes of the phasors of the zone input currents taking into account the status signals of the currents, i.e. applying the dynamic bus replica of the protected bus zone. Both differential and restraining currents are scaled to the maximum rated primary current as explained above.

The “maximum of” definition of the restraining signal biases the relay toward dependability without jeopardizing security as the relay uses additional means to cope with CT saturation on external faults. An additional benefit of this approach is that the restraining signal always represents a physical – compared to an average or “sum of” – current flowing through the CT that is most likely to saturate during given external fault. This brings more meaning to the breakpoint settings of the operating characteristic.

5. ENHANCED SECURITY

In order to enhance the performance of the relay, the differential characteristic is divided into two regions having diverse operating modes as shown in Figure 4.

The first region applies to comparatively low differential currents and has been introduced to deal with CT saturation on low-current external faults. Certain distant external faults may cause CT saturation due to extremely long time constants of the DC component or multiple autoreclosure shots. The saturation, however, is difficult to detect in such cases. Additional security is permanently applied to this region without regard to the saturation detector.

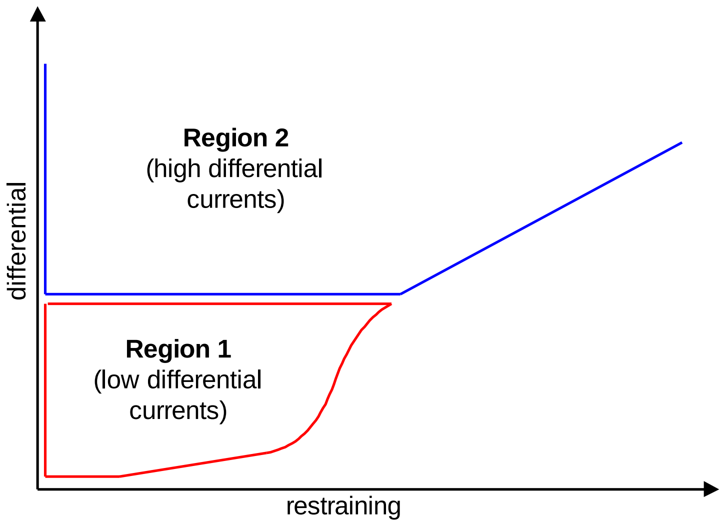


FIGURE 4: TWO REGIONS OF THE DIFFERENTIAL CHARACTERISTIC

The second region includes the remaining portion of the differential characteristic and applies to comparatively high differential currents. If, during an external fault, the spurious differential current is high enough so that the differential–restraining current trajectory enters the second region, then saturation is guaranteed to be detected by the saturation detector.

The relay operates in the 2-out-of-2 mode in the first region of the differential characteristic. Both differential and directional principles must confirm an internal fault in order for the biased differential element to operate.

The relay operates in the dynamic 1-out-of-2 / 2-out-of-2 mode in the second region of the differential characteristic. If the saturation detector does not detect CT saturation, the differential protection principle alone is capable of operating the biased differential element. If CT saturation is detected, both differential and directional principles must confirm an internal fault in order for the biased differential element to operate.

Because of diverse operating modes in the first and second regions of the differential characteristic, the user gains double control over the dependability and security issues. The first level includes slopes and breakpoints of the characteristic with regard to the amount of the bias. The second level includes control over the split between the first and second regions of the characteristic.

The unbiased differential element responds to the differential current alone. The saturation detector and directional element do not apply to the unbiased differential element.

6. DIRECTIONAL PRINCIPLE

For better security the relay uses the current directional protection principle to dynamically supervise the main current differential function. The directional principle is in effect permanently for low differential currents (region 1 in Figure 4) and is switched on dynamically for large differential currents (region 2 in Figure 4) by the saturation detector upon detecting CT saturation.

The directional principle responds to a relative direction of the fault currents. This means that a reference signal, such as bus voltage, is not required. The directional principle declares that: a) if all of the fault currents flow in one direction the fault is internal; or; b) if at least one fault current flows in an opposite direction compared with the sum of the remaining currents the fault is external.

The directional principle is implemented in two stages.

First, based on the magnitude of a given current, it is determined whether the current is a fault current. If so, its relative phase relation has to be considered. The angle check is not initiated for the load currents as the direction will be out of the bus even during internal faults.

Second, for – and only for – the selected fault currents the phase angle between a given current and the sum of all the remaining currents is checked. The sum of all the remaining currents is the differential current less the current under consideration. Therefore, for each, say p-th, current to be considered the angle between the phasors I_p and I_D-I_p is to be checked.

Ideally, during external faults the said angle is close to 180 degrees (Figure 5); and during internal faults – close to 0 degrees (Figure 6).

External Fault Conditions

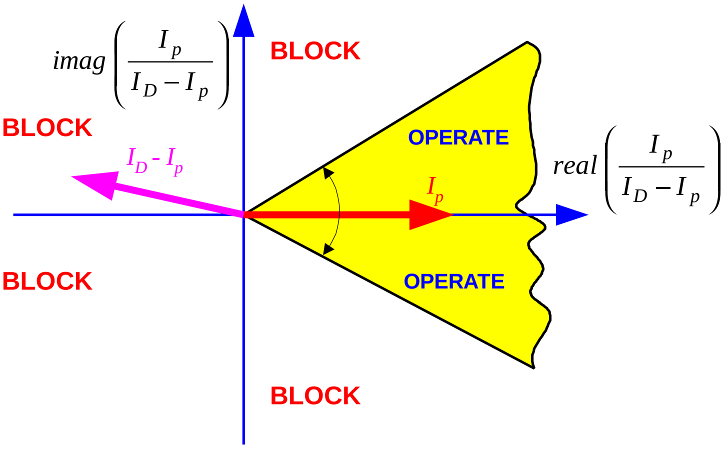
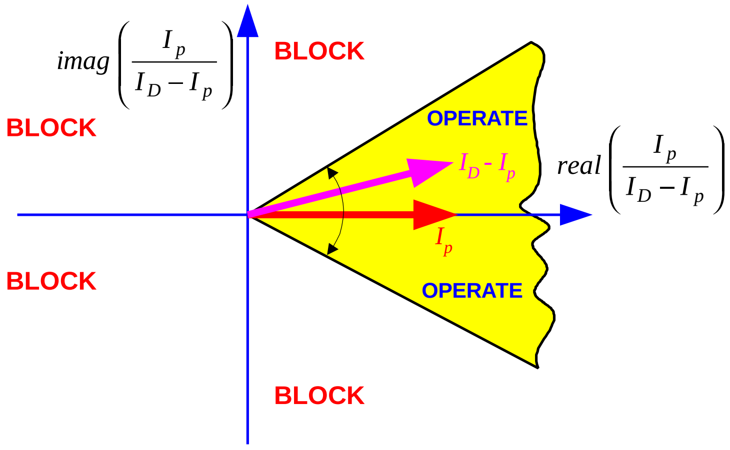


FIGURE 5: DIRECTIONAL PRINCIPLE DURING EXTERNAL FAULTS



Internal Fault Conditions

FIGURE 6: DIRECTIONAL PRINCIPLE DURING INTERNAL FAULTS

The relay algorithm calculates the maximum angle for the considered currents and compares it against a fixed threshold of 65 degrees. The maximum angle is available as an actual value in the relay MMI. The flag indicating whether or not the directional protection principle is satisfied is available as a FlexLogic^{TM} operand.

7. SATURATION DETECTOR

The saturation detector mechanism takes advantage of the fact that any CT operates correctly for a short period of time even under very large primary currents that would subsequently cause a very deep saturation. As a result of that, in the case of an external fault the differential current stays very low during the initial period of linear operation of the CT's, while the restraining signal develops rapidly. Once one or more CT's saturate, the differential current will increase. The restraining signal, however, yields by at least few milliseconds. During internal faults both the differential and restraining currents develop simultaneously. This creates characteristic patterns for the differential – restraining trajectory as depicted in Figure 7.

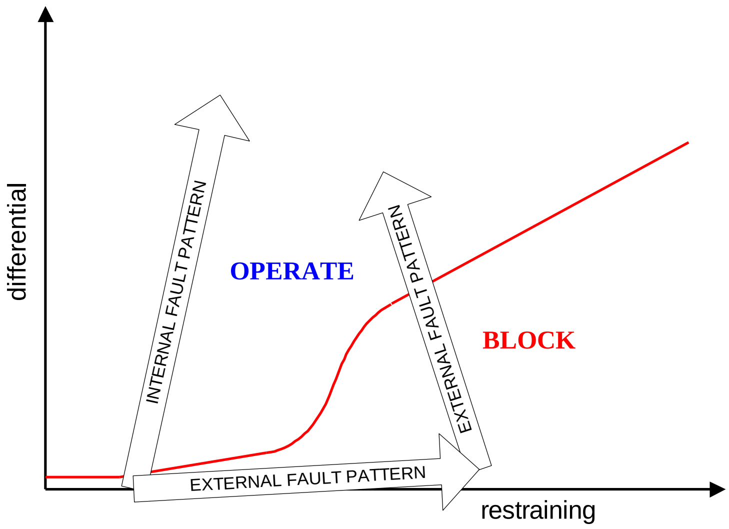


FIGURE 7: CT SATURATION: INTERNAL AND EXTERNAL FAULT PATTERNS

The CT saturation condition is declared by the saturation detector when the magnitude of the restraining signal becomes larger than the higher breakpoint (HIGH BPNT) and at the same time the differential current is below the first slope (LOW SLOPE). The said condition is of a transient nature and requires a seal-in. A special logic in the form of a “state machine” is used for this purpose.

As the phasor estimator introduces a delay into the measurement process, the aforementioned saturation test would fail to detect CT saturation occurring very fast. In order to cope with very fast CT saturation, another condition is checked that uses relations between the signals at the waveform level. The basic principle is similar to that described above. Additionally, the sample-based stage of the saturation detector uses the time derivative of the restraining signal (di/dt) to better trace the saturation pattern shown in Figure 7.

It is worth emphasizing that the saturation detector although having no dedicated settings, uses the main differential characteristic for proper operation. The operation of the saturation detector is available as the FlexLogic^{TM} operand BUS Z1(2) SAT.

8. OUTPUT LOGIC

The biased differential characteristic uses the output logic shown in Figure 9.

For low differential signals, the biased differential element operates on the 2-out-of-2 basis utilizing both the differential and directional principles.

For high differential signals, the directional principle is included only if demanded by the saturation detector (dynamic 1-out-of-2 / 2-out-of-2 mode). Typically, the directional principle is slower, and by avoiding using it when possible, the B30 gains speed.

The dynamic inclusion/exclusion of the directional principle is not applied for the low differential currents but is included permanently only because it is comparatively difficult to reliably detect CT saturation occurring when the currents are small, i.e. saturation due to extremely long time constant of the d.c. component or due to multiple autoreclosure actions.

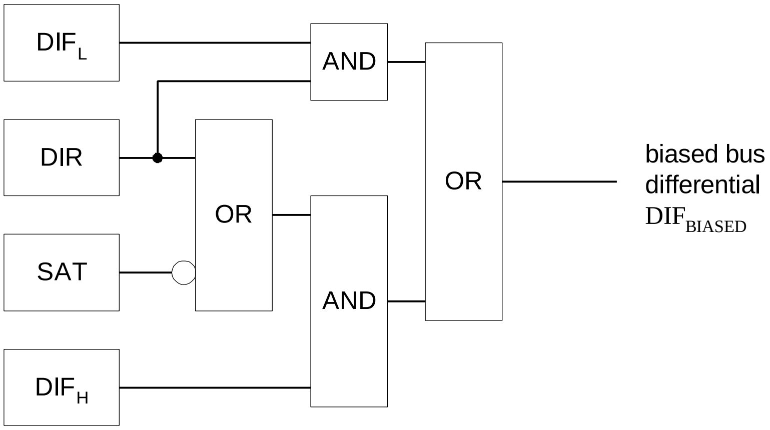


FIGURE 9: OUTPUT LOGIC OF THE BIASED DIFFERENTIAL PROTECTION

9. APPLICATION EXAMPLE

Figure 10 shows a double bus arrangement with NORTH and SOUTH buses, five circuits and a tiebreaker. The C-1 circuit is connected to the NORTH bus; the C-2, C-3 and C-4 circuits can be routed to either bus via the switches S-1 up to S-6; the C-5 circuit can be connected to either bus via the B-5 and B-6 breakers.

The NORTH bus differential zone is bounded by the following CT's: CT-1, CT-2 (if S-1 closed), CT-3 (if S-3 closed), CT-4 (if S-5 closed), CT-5 and CT-8. The SOUTH bus differential zone is bounded by the following CT's: CT-2 (if S-2 closed), CT-3 (if S-4 closed), CT-4 (if S-6 closed), CT-6 and CT-7.

The NORTH bus protection operates the following breakers: B-1, B-2 (if S-1 closed), B-3 (if S-3 closed), B-4 (if S-5 closed), B-5 and B-7.

The SOUTH bus protection operates the following breakers: B-2 (if S-2 closed), B-3 (if S-4 closed), B-4 (if S-6 closed), B-6 and B-7.

To provide the bus differential zoning as described above eight currents need to be measured. Consequently, the protection cannot be accomplished by one B30 relay. However, as each bus has not more than six connections, two B30 relays can be used.

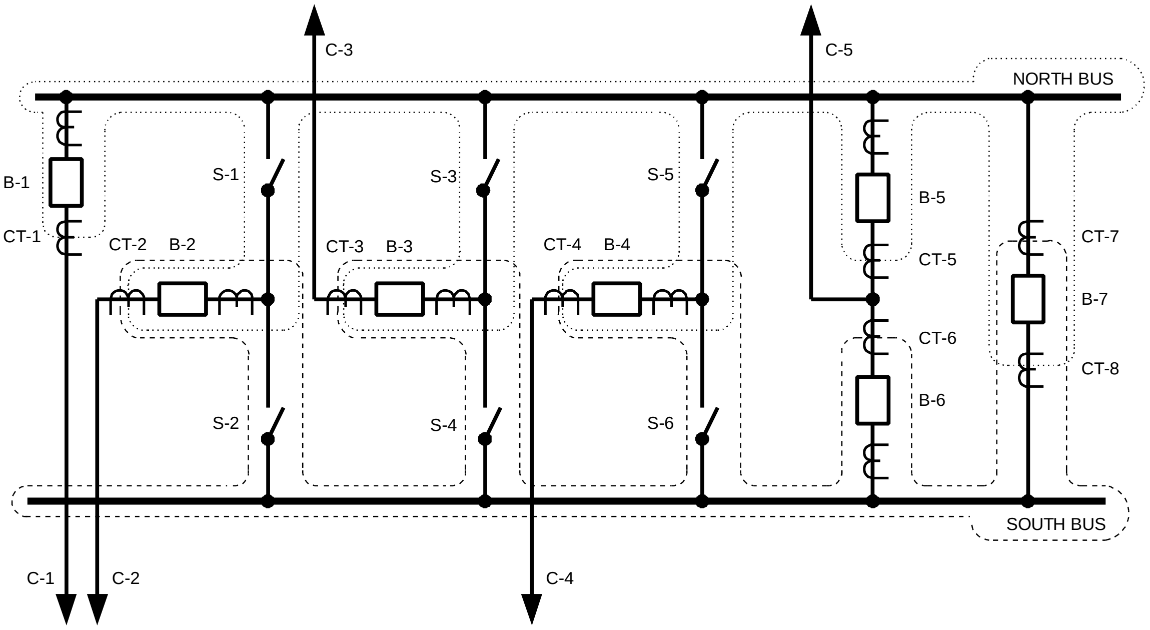


FIGURE 10: SAMPLE BUS CONFIGURATION

10. CONCLUSIONS

Busbar faults are dreadful incidents in the operation of an electrical network. Failure to clear an internal bus fault results in extensive damages to the substation and can make the whole system unstable. On the other hand, it is equally harmful a mal operation of a busbar relay, since an important node is removed from the network which can also upset the operation of the entire power system.

High-speed busbar protection in large electrical networks is an essential element in maintaining stability. The concentration of energy in electrical buses give rise to the great problem associated with busbar protection: CT saturation.

Whatever busbar protection principle is used, the busbar relay must fulfil especial high requirements with respect to security, selectivity, operating speed and adaptability to changing busbar configurations.

A new low impedance current restrained dual slope biased bus differential relay provides these requirements. The relay has dedicated mechanisms to detected CT saturation; the tripping logic includes supervision by current directional element.

Bibliography

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