SPECIAL CONSIDERATION OF FEEDER PROTECTION FOR BREAKER-AND-A-HALF CONFIGURATIONS

G. Steynberg

Siemens AG; Energy Sector, Energy Automation, Nuremberg

1. INTRODUCTION

The breaker-and-a-half configuration has always been preferred in some regions, for example USA, and is gaining popularity in other parts of the world. The motivation for or against breaker-and-a-half configurations is not driven by the protection technology. On the contrary, the protection technology must ensure that the breaker-and-a-half scheme has the same reliability as alternative configurations would have. This paper will address the feeder protection, which is presented with unique problems in this configuration as two circuit breakers must be tripped and measurement from two sets of current transformers must be considered. The aspects of current transformer errors, in particular saturation, and auto re-closure schemes are analyzed in this paper.

Typical breaker-and-a-half configuration

In Figure 1 below the connection of a single intelligent electronic device (IED) to the process interface of a breaker-and-a-half bay is shown in schematic form.

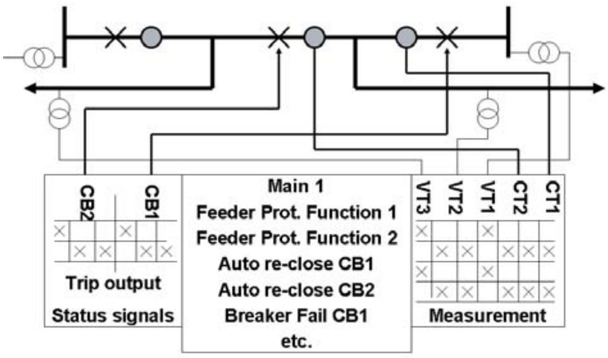

Figure 1: Connection of IED

There is a substantial amount of information, measurements and status signals, which are connected to the IED. The challenge of managing this task in a user friendly manner will be covered in section 5 of this paper.

CT related difficulties with breaker-and-a-half configuration

The typical arrangement of the current transformers with breaker-and-a-half schemes is shown in Figure 2 below. In addition to the usual difficulties associated with CT errors, this arrangement introduces an additional aspect when only one of the two CT's goes into heavy saturation during an external fault (F1).

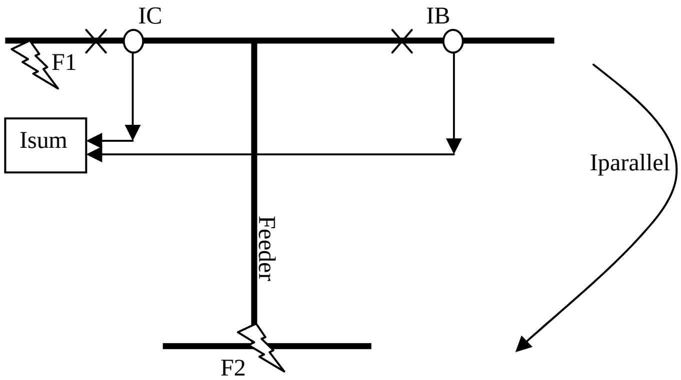

Figure 2: CT connection

Fundamentally there are two methods to connect the cores of the two sets of CT.

External summation: When the cores of the two CT sets are connected in parallel (with suitable polarity), the resultant measured current will be the sum of two currents flowing in the CTs. This sum-current corresponds to the current flowing into the feeder and is therefore used for the protection and other functions to represent the feeder current. This method is commonly used, as the conventional protection device only has facility for connection of one set of CT measurement.

Separate connection (internal summation): In the event that the device to which the currents are connected has sufficient measuring inputs, the two sets of CT may also be separately connected to the device. In this case the summation is carried out in software internally. This has the advantage that protection functions that require the individual current measurement (e.g. breaker fail) can also be integrated in the device. Separate recording of the currents for fault analysis is also possible. For differential protection the restraint current may also be calculated based on both currents separately, to ensure correct stability during external faults. In case of distance (and other directional) protection functions, an additional directional restraint, which is required during saturation of only one of the two CTs, can then be incorporated.

The aspects of CT connection with differential and distance protection are covered in sections 2 and 3. Section 4 presents a model used for simulation of unequal CT saturation. Results of the simulation are then used to illustrate that the CT saturation condition requires add-on directional stabilization for the distance protection.

Single IED for bay protection in breaker-and-a-half configuration

The final topic covered in the paper addresses a structured approach for integration of multiple functions in a single IED, in conjunction with breaker-and-a-half configurations. Section 5 will show the grouping of logical functions, multiple instances and structured allocation of measuring points for a user friendly engineering of protection for the configuration at hand.

2. CT CONNECTION WITH DIFFERENTIAL PROTECTION IN BREAKER-AND-A-HALF CONFIGURATION

If the differential protection measures both currents IB and IC separately, as illustrated in Figure 3 below, it can treat the breaker-and-a-half end as two separate infeeds. Calculation of the differential (Idiff) and restraint (Irest) current will then be done as usual. Consideration of individual CT saturation is no problem to the diff protection, if it is configured properly. A differential protection system using the partial summation technique [1] will also not increase the communication requirement as only the resultant differential and restraint currents are transmitted after local computation.

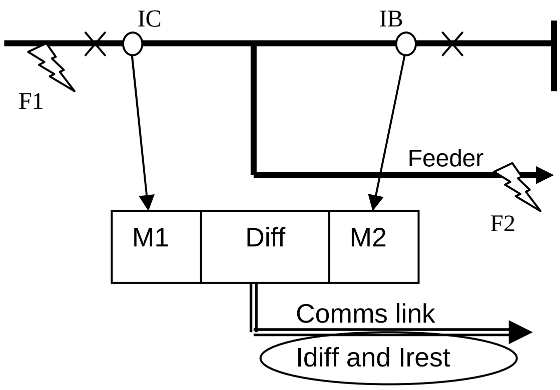

Figure 3: Diff protection with separate measurement of both CT currents

Figure 4 below shows the current distribution during a reverse fault on the breaker-and-a-half side (left). For the differential protection it corresponds to a three terminal application. Summation of currents I1, I2 and I3 yields zero as diff current, which results in stable response. With single measurement of external summated current, the result is also stable as Isum equals –I3 in this case.

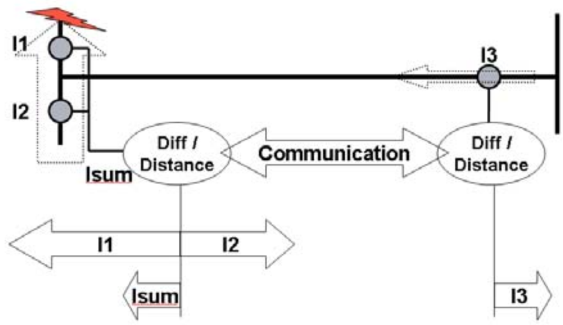

Figure 4: Current distribution - reverse fault

If during this fault condition the CT with the largest current saturates (I1), the situation is different as shown in Figure 5 below:

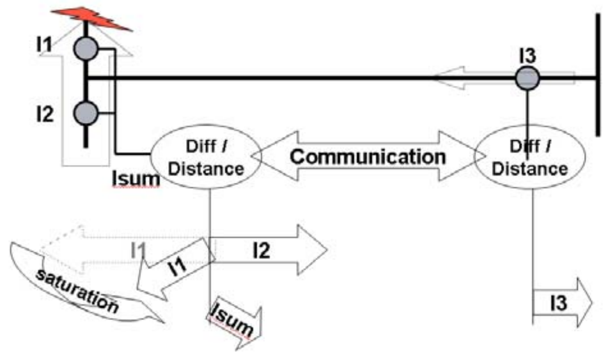

Figure 5: Current distribution - reverse fault and saturation of CT1

With a single current measurement of the externally summated CT signals, the left hand relay would only measure Isum which has a similar orientation to I3, the differential current would therefore almost correspond to the sum of magnitudes of I3 and Isum. A trip by the differential protection would occur unless some additional measures are applied. The separate measurement of I1 and I2 will ensure sufficient restraint current for stable differential protection.

Lets consider the simpler cost saving compromise for differential protection with external summation of the two CT currents. Thereby a relay with only one set of current measuring inputs can be applied. To overcome the described single CT saturation problem, a signal distortion measurement is done. The principle of this add-on restraint due to signal distortion is shown in Figure 6 below. The distorted waveform is sampled and applied to a numeric measurement with fundamental waveform filter. The resultant measured signal therefore corresponds to the shown fundamental frequency sine wave. The delta between the distorted input signal and the computed sine wave is shown as shaded area. This area corresponds to the level of signal distortion and determines the amount of add-on restraint that is necessary to avoid incorrect differential measurement.

Even the worst case CT saturation will be detected with this function which then dynamically increases the restraint current to avoid incorrect tripping at all ends of the differential protection.

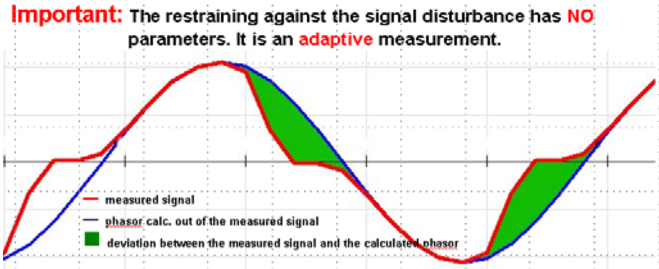

Figure 6: Add on restraint for secure diff protection and CT saturation

3. CT CONNECTION AND DISTANCE PROTECTION IN BREAKER-AND-A-HALF CONFIGURATION

In general, the CT and VT connection for distance protection is as shown in Figure 7 below. The protection for the feeder must use the sum of the currents IC and IB for the protection function. For the external reverse fault shown at F1, the resultant summated current is approximately zero, if there is no significant remote in-feed, even if the individual currents IC and IB are large. Individual errors from the two CT measurements may therefore constitute a significant portion of the resultant summated current. This condition together with the small measured voltage due to the fault F1, which may be very close to the relay location, can result in incorrect operation of the distance protection during this reverse fault.

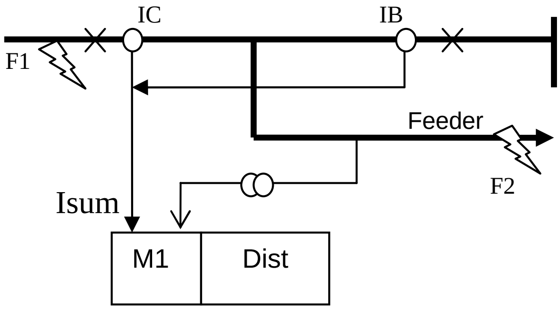

Figure 7: Distance protection with external summation of both CT currents

Problem case: external (reverse) fault with CT saturation and weak infeed from remote end

During the fault at F1 in Figure 7, with no in-feed from remote end:

$$IB = -IC \qquad Isum = 0$$

If during this fault there is a CT error present (Ierr), because of the large current flowing from the right side bus causing saturation of CT measuring IC or IB, the total error current will appear as summated current:

$$Isum = Ierr$$

During a close in fault when U is approximately zero an incorrect trip by the distance protection, as well as other directional protection functions, is possible due to incorrect direction measurement (Ierr can assume any relative direction).

For distance protection that does not measure the two currents separately, a minimum current threshold, set adove the maximum expected error current, should be applied for close in faults (zone 1) to avoid the risk of wrong trip during close in reverse fault, with no in-feed from remote end as in this case the only measured current corresponds to the CT error.

Add-on directional stabilization based on comparison of both measured currents

If the distance protection measures both currents separately as shown in Figure 8, an add-on directional stabilization is possible to avoid wrong trip during reverse fault with CT saturation.

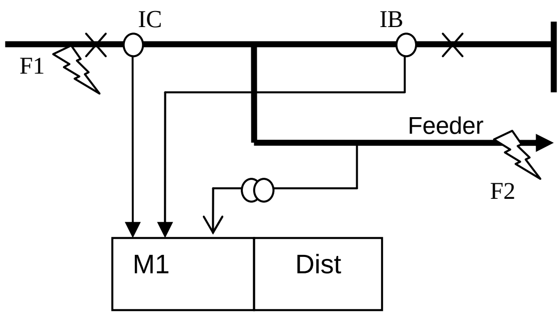

Figure 8: Distance protection with separate measurement of both CT currents

The fundamental principle of the add-on stabilization can be described as follows: During the fault at location F1 the current IB will be equal to –IC if there is no in-feed from remote end. Note that remote in-feed current contributes to correct direction measurement. With sufficient remote in-feed the add-on directional stabilizing is not required.

Assume that there is saturation only at current measurement IB. This corresponds to the problem case, as the resultant summated current will indicate a forward fault. By applying appropriate filtering to the measured currents, the magnitude of IB (saturated) will be less than that of IC which is not affected by the CT saturation. The magnitude of Isum will correspond to the degree of saturation but will be less than IC which corresponds to the full unsaturated fault current. Note that saturation by both CT sets during the external fault alleviates the problem by resulting in a smaller summated error current. Note also that the add-on directional stabilizing should only be applied when both individual measured currents exceed the threshold above which saturation could be expected. This ensures that directional sensitivity during remote and high resistance faults is not affected by this measure.

The add-on directional stabilizing also requires a separate direction measurement for both measured currents. A typical expected result during reverse fault (F1) with saturation of the centre CT would then be as follows:

IB = 10 A with forward direction
IC = 6 A with reverse direction
Isum = 4 A with forward direction

A similar current distribution can however also occur for a forward fault at F2, when substantial fault current can flow via a parallel path to the remote station. The differentiation between reverse and forward fault with CT saturation must therefore be done dynamically, using the duration (approx ¼ cycle) after fault inception before CT saturation occurs.

The necessity of the add-on directional stabilizing will be demonstrated with the simulation in the next section. By simulation of a fault at F2, the similarity to the fault at F1 with CT saturation is shown. The current waveforms also illustrate the ¼ cycle period during which a secure reverse decision can be made.

4. MODEL USED TO SIMULATE STABILITY DURING EXTERNAL FAULT WITH CT SATURATION

Description

The computer based simulation was done with NETOMAC® using the network shown in Figure 9. A CT model was used to simulated saturation in the modeled current waveform of the centre CT.

Initially the external fault position (F1) is modeled and both current measurements recorded for analysis.

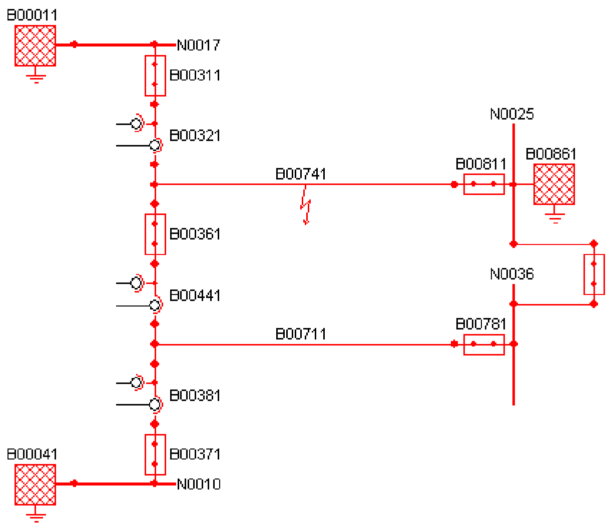

Figure 9: Netomac® model used for simulation

The protected feeder is B00741, and the strong infeed is B00011 (8GVA). This will result in large through fault current during external faults on B00711. The remote infeed (B00861) is weak and does not contribute any significant fault current.

Simulated fault condition and test results

The close external reverse fault (F1) is simulated at a distance of 1km along the parallel line. The resultant current waveforms are shown in Figure 10 below:

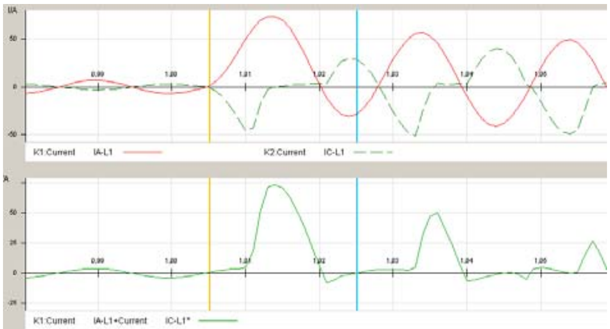

Figure 10: Current waveform during close in reverse fault (F1)

In the top of Figure 10 the current IB (solid line) and IC (dashed line) are shown. The bottom trace shows Isum. The severe saturation of IC after a ¼ cycle can be seen. Under normal circumstances saturation after such a short time would not occur with properly dimensioned CT. Note the position of the two cursors in the diagram. The left cursor marks fault inception while the right cursor marks 1 cycle after fault inception. In Figure 11 below the phasors of the currents in Figure 10 are shown based on a full cycle DFT filter (filter window is the interval between the cursors in Figure 10) used to calculate the fundamental component:

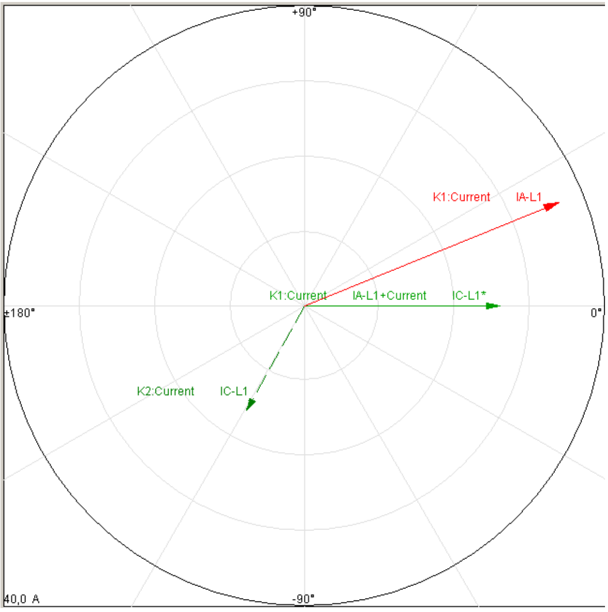

Figure 11: Filtered fundamental component amplitude during close in reverse fault (F1)

The peak level of the summated current (on real axis in Figure 11) which corresponds to the CT error is 26.1A and is reached after exactly one cycle of fault current flow. The magnitude of all three currents and their direction is as follows:

IB = 36.1 A with forward direction
IC = 15.9 A with reverse direction
Isum = 26.1 A with forward direction

This corresponds to the expected relationship stated earlier.

Check of add on stabilization during forward fault

To check how the add-on directional stabilization can be applied to not incorrectly stabilize during a forward fault, the following condition is simulated: Fault at remote bus with a strong parallel connection. The fault current in the parallel line will be approximately twice that in the faulted line. This corresponds to two parallel feeders that are connected to the same bus at remote side and the total local infeed is flowing through one diameter – this exceeds most practical applications and may therefore be considered as a severe real worst case condition.

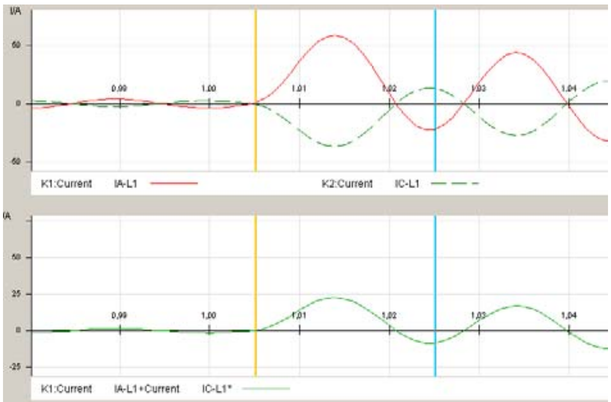

Figure 12: Current waveform during remote fault with no CT saturation (F2)

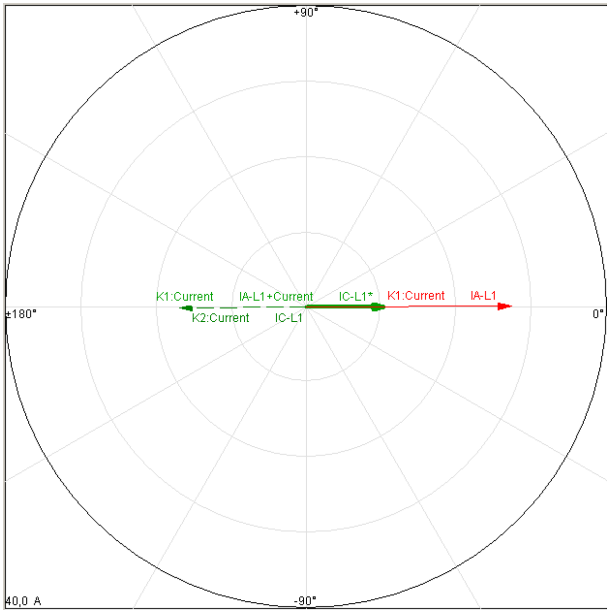

Figure 13: Filtered fundamental component amplitude during remote forward fault (F2)

The currents in Figure 12 are either in phase or in phase opposition, as shown in Figure 13, with the following magnitudes based on the same measurement as described above.

IB = 27.4 A with forward direction
IC = 17.0 A with reverse direction
Isum = 10.4 A with forward direction

When comparing Figure 11 and 13 it is apparent that the three shown currents have a very similar relationship. The relative magnitudes of the currents in Figure 13 are almost the same as during the reverse fault with saturation and the directions are exactly the same for all three currents. Steady state add-on stabilization is therefore limited when there is a strong parallel connection to the remote bus. The solution is to make the add-on stabilization dynamic. It must use the initial fault condition prior to saturation to determine that the fault is reverse. In Figure 10 and 12 this corresponds to the ¼ cycle immediately after the left cursor. Here

Isum equals zero (load) during the reverse fault (Figure 10) while there is substantial Isum during the forward fault (Figure 12).

Effect of add on stabilization

The add-on stabilization for the reverse fault in Figure 10 indicates a reverse fault because Isum is approximately zero (<10% IB or IC) during the first ¼ cycle. Also IB and IC are above the threshold at which saturation is possible. If this had not been the case, the distance function would detect the fault in forward Zone 1 as the measured impedance is approximately 0.34 Ohm at an angle of 63° in the 1^{st} quadrant. Generally this would be a clear zone 1 trip! The add-on directional stabilizing prevents this.

During the forward fault in Figure 10 the value of Isum is greater than 10% IC (60%) so that the add-on directional stability does not respond. The forward fault is correctly cleared.

5. PROTECTION SCHEME DESIGN WITH SINGLE IED FOR BREAKER-AND-A-HALF CONFIGURATION

The breaker-and-a-half configuration contains a number of measuring points that are required for the various protection functions in the device. For a feeder protection both circuit breakers must also be operated by the protection functions. This operation consists of trip signal following fault detection and possibly an auto re-closure signal. In Figure 1 the complexity of this arrangement is shown based on a single main protection device with multiple protection functions integrated.

For the user the task of configuring such a device is daunting. On the one hand it requires full flexibility in allocation of measuring points and trip outputs, while on the other hand the number of configuration points to satisfy this flexibility results in an unacceptable setting quality. The solution is to create a structure with numbered measuring points and logical grouping of functions. In Figure 14 below this is shown for the most common protection functions applied on a transmission feeder.

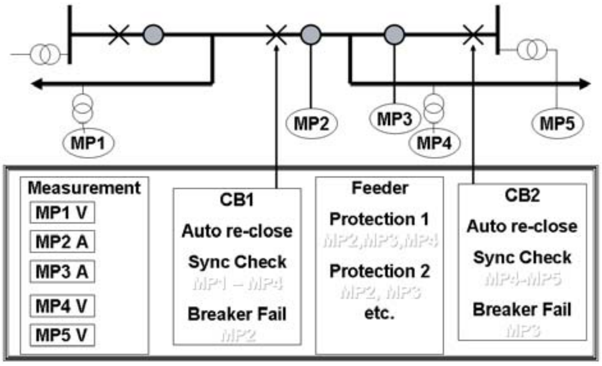

Figure 14: Grouping of functions and measuring points in an IED

The measuring points are numbered so that "measuring nodes" can be formed to satisfy the individual protection functions (and operational measured values). For each circuit breaker a separate breaker group is formed. It not only provides all the peripheral signals associated with the circuit breaker, it also contains the protection functions dedicated to the breaker such as auto re-close, sync check and breaker fail.

Assignments for the protection functions will therefore be twofold, on the one hand the measuring points must be set, and on the other hand the associated breaker group(s) must be configured. This is shown for a distance protection function in the diagram below:

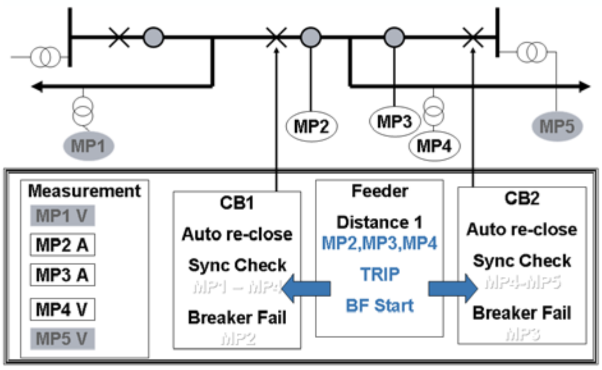

Figure 15: Assignment of measuring points and internal signal exchange

For the distance protection the relevant measuring points must be assigned. As more than one current is assigned, the function must be capable of properly combining the two measured signals. The trip decision by the distance function must be routed to both associated circuit breakers. How the circuit breaker responds (1 or 3 pole trip) depends on its configuration. It is also possible that the two circuit breakers respond differently, e.g. the centre CB could trip 3 pole while the bus CB trips single pole. This however is not part of the individual protection (distance) function configuration, it belongs into the circuit breaker configuration as shown below.

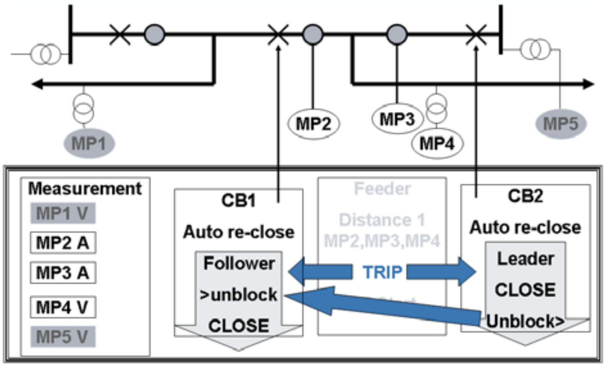

Figure 16: Multiple AR functions with internal co-ordination

Each of the circuit breakers, here CB1 and CB2 has its own function "package" which includes functions such as auto re-close, breaker fail, sync check etc. The "CB package" also contains all outputs to the CB as well as the relevant feed-back signals such as auxiliary contacts and status information.

Ultimately, the concept of separating logical functions (logical node) and then grouping them to mirror the application (logical device) is in accordance with the IEC61850 concept. Within this environment, the application of multiple instances of logical nodes such as auto re-close, breaker fail, sync check and circuit breaker provides a powerful, compact and simple method to apply a multiple function device in a complex scheme such as breaker and a half. Routing of signals between the logical nodes is programmed into the device with software tools, thereby reducing construction, testing and documentation overheads.

Auto re-close scheme design for breaker and a half

The most obvious aspect of the breaker and a half scheme in terms of re-closing is the fact that two circuit breakers must be operated. Although a number of different methods are used for this purpose they may be summarized as follows:

The protection functions trip both circuit breakers. In general, if single pole tripping is applied, both circuit breakers are tripped single pole. In some cases the centre breaker is tripped three pole irrespective of the trip method for the busbar side circuit breaker.

The reclose dead time may be a fixed time, or adaptive depending on the remote side re-closing. Following the "dead time" the leader circuit breaker is reclosed. The leader may be the centre or busbar side circuit breaker; usually it is the busbar side breaker. Co-ordination between leader and follower is done internally by means of a release signal from the leader when it has successfully reclosed.

Conclusion

For the breaker-and-a-half configuration the risk of bad tripping by differential and distance protection functions deserves special attention. The paper has shown that CT saturation can cause bad operation by both measuring principles if the application is not correctly done. The proposed add-on directional stabilizing for distance protection must be considered where sufficient remote in-feed cannot always be guaranteed.

To cope with the complexity of the breaker-and-a-half configuration in combination with modern multifunctional IED protection devices a structure with grouped functions along with suitable configuration software is essential to ensure a high quality in the scheme design at acceptable engineering cost.

REFERENCES

1. SIPROTEC 7SD52/53 V4.60 Line Differential Protection: C53000-G1176-C169-2 Manual Siemens AG

2. Application of Distance and Line Current Differential Relays in Breaker-and-a-Half Configurations: B. Kasztenny and I. Voloh.