Rough Balance Busbar Protection and Breaker Failure Protection for the HK Electric’s Distribution Network

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Abstract – Primary distribution substation busbar forms an electrical node where incoming sources and outgoing circuits come together, feeding in and sending out power directly to customers. If a busbar fails or trips, it will lead to the supply interruption to a large number of customers fed by the outgoing circuits connected to the busbar. The interruption time will be much longer because the supply restoration can only be done at downstream level through multiple switchings. Therefore, a reliable and discriminative busbar protection is crucial to protect this important piece of equipment in the distribution network and to achieve high supply reliability.

Proper protection design of a distribution network should also cater for circuit breaker failure when an external fault occurs. When this happens to a circuit breaker connected to a busbar, tripping out of the busbar to clear the fault is inevitable. For this reason, breaker failure protection is normally incorporated into the busbar protection scheme of a primary distribution substation as a total solution.

This paper describes the HK Electric’s distribution protection system that employs a simple yet effective rough balance differential principle to achieve busbar protection and breaker failure protection with proper fault discrimination. The paper also compares the merits and drawbacks of different busbar and breaker failure protection schemes adopted by us and some other utilities.

Keywords: Rough balance busbar protection, Circuit breaker failure protection, Frame earth leakage protection, Interlock overcurrent (ILOC) protection, IDMTL

1. Introduction

The Hongkong Electric Co. Ltd. (HK Electric) was founded in the year 1890. It is one of the oldest electricity supply companies in Asia. At present HK Electric has one power station situated at the western tip of Lamma Island where electricity is generated and transmitted to Hong Kong Island and Apleichau Island at 275kV. Electricity is stepped down either directly or via intermediate 132kV network to 11kV or 22kV at primary zone substation (Z/S) for feeding the distribution network.

The HK Electric 11kV distribution system is a pure cable network. Two or more 11kV feeders from Z/S’s are interconnected to form a ‘feeder group’. They are normally operated as open ring circuits with ‘normal-open’ points at focal locations in the feeder group. 11kV cable fault in the ring will be cleared by the respective feeder circuit breaker (CB) at Z/S equipped with two-pole overcurrent and single-pole earth fault (OCEF) protection. Supply will then be restored from backup sources.

In a typical Z/S, there are four zone transformers each feeding one 11kV busbar. The four 11kV busbars are arranged to form a ring with the use of bus-section (BS) or bus-interconnector (BI) breakers. A typical Z/S configuration with all BI breakers is shown in Fig. 1.

![Fig. 1. Typical Z/S configuration.](image)

Normally, the busbar ring is split into two sections with each section being fed by two zone transformers running in parallel. For Z/S’s constructed after 1989, a maximum of three zone transformer windings can operate in parallel such that when one of the four transformers is taken out of service, the remaining three transformers can operate in parallel to supply all four busbars. Tripping of one of the two/three zone transformers operating in parallel will therefore not result in loss of supply to customers and the
resilience of distribution network against any transmission/zone transformer fault is very high.

2. Rough Balance Busbar Protection

Consistent with the open ring network, HK Electric adopts non-unit protection design in the 11kV distribution system based on the short time fault ratings of the primary apparatus and grading between successive stages of protective devices, which are typically ‘Inverse Definite Minimum Time Lag’ (IDMTL) OCEF protection.

The rough balance busbar protection is the main protection for the 11kV busbars at HK Electric Z/S’s. The busbar protection measures the currents at all in-feed points to the busbar, which are roughly balanced to give the total busbar load/fault current, but will cancel out any current flows to load/faults outside the protected zone. The rough balance CT’s are only installed on the transformer incomer, BI and BS circuits. The secondary outputs of these CT’s are connected in parallel to the rough balance busbar protection which senses the busbar load current during normal condition and remains stable.

When there is a fault on the busbar or its outgoing feeders, the busbar protection will sense the full fault current, irrespective of the location and number of the feeding transformer(s), being in-zone or out-zone. The rough balance busbar protection will then initiate the tripping of fault in-feed sources into the busbar simultaneously, including the transformer 11kV incomer, BS and BI CB’s (and the capacitor bank feeder if it is connected to the busbar) according to IDMTL current setting.

The CT and tripping arrangement of rough balance busbar protection for a typical 132/11kV Z/S is shown in Fig. 2.

![Fig. 2. CT and tripping arrangement of 11kV rough balance busbar OCEF protection.](image)

In addition to providing the main protection to the busbar, the rough balance protection can serve as the first backup protection for the 11kV feeder protection as well as circuit breaker failure protection (CBF) for the outgoing feeder circuits. It is a simple and economical protection scheme since no busbar protection CT’s are required on 11kV feeder circuits. It does not impose stringent requirement on the CT’s and does not require sophisticated busbar CT selection schemes.

The main disadvantage of rough balance scheme is that the busbar fault clearance time is moderate, typically around 0.9 second. However, it should be noted that the frequency of distribution feeder faults and associated breaker failure scenarios are much higher than switchgear busbar faults. The benefit of serving the backup protection and breaker failure protection for feeder faults in the same rough balance scheme should outweigh its relatively slower busbar fault clearance time as compared with other busbar protection schemes elaborated below.

3. Other Types of Busbar Protection

3.1 Exact balance busbar protection

The exact balance busbar protection is a unit type protection with CT’s installed on all associated circuits connected to the protected busbar. Currents entering and leaving the protected zone are added up to give zero output under normal condition or full fault current under in-zone fault condition. This can provide fast operation at a low fault setting under through fault condition. A proper voltage setting which is greater than the voltage likely to develop across the relay during maximum through fault condition shall be selected to ensure protection stability.

The CT arrangement of the exact balance scheme is shown in Fig. 3. This type of busbar protection scheme usually employs a high impedance relay to achieve stability under through fault condition. A proper voltage setting which is greater than the voltage likely to develop across the relay during maximum through fault condition shall be selected to ensure protection stability.

![Fig. 3. CT arrangement of exact balance busbar high impedance differential protection.](image)
The main disadvantage of such scheme is the requirement for dedicated CT with high performance (Class PX) for all associated circuits connecting to the busbar. This will impose a significant cost and may create space problem to accommodate such CT in modern standardized distribution switchgear.

Furthermore to avoid relay mal-operation due to earth loop current when a feeder cable is earthed at both ends during cable maintenance, repeat relays that mimic the actual status of the switchgear’s earthing switch by its auxiliary contacts are required to short and disconnect the associated CT from the busbar protection scheme. The repeat relay contacts in the CT path may compromise the dependability, jeopardize security and complicate the protection scheme with extra costs.

The fast operation of the exact balance scheme in a pure distribution cable network will also create its own problem to be solved. Due to the high X/R ratio of the zone transformer impedance, there will be a large DC component in the 3-phase fault current. Distribution CB’s are not normally designed and type tested for breaking fault current with a large DC component. To avoid damaging the CB, the tripping is deliberately delayed by adding external timer relays and this will again complicate the protection scheme.

Finally, this scheme cannot provide feeder backup protection and detect feeder CBF condition. Separate protection schemes are required, usually by sequential tripping of the BI’s followed by in-feed transformer and an overall tripping time over 1.5 seconds is expected.

3.2 Frame earth leakage protection

This scheme involves the measurement of fault current flowing from switchgear frame to earth. All the metal parts of the switchgear must be insulated from the earth to avoid spurious currents being circulated. A CT is installed at the earthing cable connecting between the frame and the earthing point. The CT energizes an instantaneous ground fault relay to trip the switchgear, typically all the CB’s connected to the busbar.

HK Electric has adopted this type of busbar protection for the 525V DC switchgear at traction substations. Based on past experience, some issues that affect the reliability of the protection scheme are summarized below:

a. Low insulation between the switchgear frame and earth will form a shunt path for the earth fault current which normally flows through the CT, thus reducing the sensitivity of the protection.

b. Mal-operation of the relay may also happen when external electrical energy is discharged through the panel to the earth inadvertently.

c. It is difficult to locate and repair the low insulation fault between the metal frame and substation earth.

d. Separate protection schemes are required to cater for feeder backup and CBF condition with significant fault clearance time.

Besides, when applied to a.c. busbars, this scheme can only detect unbalance faults, i.e. it may not be effective for 3-phase-to-earth fault, which is the typical fault nature for three phase common tank distribution switchgear.

3.3 Interlock Overcurrent busbar protection (ILOC)

The Interlock Overcurrent (ILOC) busbar protection scheme [2] [3] relies on the use of numerical relays with multiple built-in characteristics. Numerical overcurrent (OC) relays are installed on all 11kV outgoing feeder circuits, and numerical directional overcurrent (DOC) relays at 11kV incomer and BI / BS circuits. The feeder OC’s are set to sense the fault currents on the feeders. The DOC on the incomer circuit is set to trip the busbar unless blocked by any of the feeder OC relays. Time coordination is required to avoid racing conditions for this scheme which is commonly in the form of definite time delay in operation.

Nowadays numerical relays can incorporate more than one protection function in the same relay and the CBF protection function can easily be enabled on the numerical OC relay. If the feeder OC fails to operate or when CBF condition is detected by the OC relay, the blocking will not be provided or will be removed to allow fast tripping of busbar protection scheme to clear the fault.

This protection scheme has a number of merits over the exact balance and frame earth leakage busbar protection. It does not require high performance and dedicated CT’s; it provides backup and CBF protection and is not restricted to earth fault.

The DOC relay installed on the incomer and BI circuits requires the busbar voltage signal to determine the fault current direction. As 11kV voltage transformer (VT) are not normally available on the 11kV BI or BS circuits, additional busbar VTs or VT buswire from the transformer incomers are required to provide this voltage signal to the DOC relay. For the more complex substation configuration like ours with a maximum of three transformers operating in parallel, the voltage selection scheme will be very complicated.

For a double-busbar configuration with multiple in-feed
transformers, bus-couplers and BS, repeat relays are required to mimic the transformer, bus-coupler and BS CB’s as well as isolator switch statuses such that the directional relays installed on the bus-couplers and BS can receive the correct polarising voltage from the associated transformer VT.

The CBF protection offered by ILOC scheme depends heavily on the communication between the OC and DOC relays. If the communication is achieved by hard wires between these relays, the number of control wirings could be numerous. In addition, single wiring defect in the VT circuit can blow the VT’s fuses and render the scheme useless. If the OC relay fails to send a blocking signal to the DOC relay, the DOC relay will trip unnecessarily for a non-busbar fault. The voltage selection scheme will also require the use of repeat relays and auxiliary contacts which further complicates the scheme and lowers the reliability of the blocking scheme.

Furthermore, directional relays usually come with VT failure (VTF) self-monitor alarm which will block the relay from operation if an unhealthy voltage is detected. If one of the voltage selection repeat relay contacts fails to switch over to the associated polarising voltage, relay operation will be blocked by VTF alarm and therefore, the relay will be inhibited from operation.

To avoid such situation, extra supervision features have to be implemented to avoid mal-operation or non-operation condition. This will further complicate the scheme and impose extra cost.

With the maturity of the IEC61850 technology and GOOSE communication, these relays can be linked by optical fibres via IEC61850 [4] and thereby eliminating the extra control wirings as well as overcoming many of the short-comings of ILOC in the future.

4. Rough Balance Busbar Protection Setting Philosophy

As pointed out at the beginning of this paper, rough balance protection as a non-unit protection has the advantages of being able to provide protection to a larger section of network and cater for backup protection and CBF condition. An uncleared feeder 3-phase fault due to either relay failure or a stuck 11kV feeder breaker will be cleared by the rough balance busbar protection in about 0.9 second. If rough balance busbar protection is not provided, the fault clearance time is much longer as fault clearance has to be achieved by 2-stage trippings of the BS / BI and the transformer incomer CB’s with separate 11kV backup protection. To achieve discriminative fault clearance, IDMTL OCEF protection with proper time grading between the upstream and downstream protection is adopted on the network. This is a complicated process and requires careful judgment.

4.1 IDMTL OCEF relay

The IDMTL OCEF relay possesses the characteristic of decreasing relay operating time with increasing relay current, that is, the higher the fault current, the faster the relay operation.

![Fig. 4. Typical Time/Current characteristic of 3-second standard IDMTL overcurrent relay.](image)

Typical time-current curves of the 3-second IDMTL relay are shown in Fig. 4.

4.2 Grading margin

In order that the minimum amount of the plant is disconnected to isolate the fault, fault discrimination has to be provided between the upstream and downstream relays so that a feeder fault should be cleared by feeder OCEF relay while upstream protection, i.e. rough balance busbar protection, should remain stable. When the feeder CB fails to clear the fault, the busbar protection will be required to operate.

The grading margin between the two successive stages of OCEF relays needs to cover the following:

a. Feeder CB interrupting time
b. Rough busbar OCEF relay overshoot time
c. Relay and CT errors for both relays under grading
d. Safety margin
It can be seen that items ‘a’ and ‘b’ are more or less constant while items ‘c’ and ‘d’ are variable depending on the relay operating times. In the grading of OCEF relays in HK Electric system, a typical grading margin of 0.4 second is used for feeder faults.

4.3 Special consideration to cater for sequential earth faults on two feeders

Since the 11kV system in HK Electric is resistive-earthed, voltage on sound phases will rise from 6.35kV up to 11kV during single-phase-to-earth fault condition. The temporary voltage stress may precipitate failure of weak points in the system, say a defective cable joint. A second earth fault may then occur before the first one is cleared. Having responded to the first fault, the induction disc of the busbar protection relay will continue to move in the presence of the second fault and thus proper grading between the busbar protection and the feeder protection (second fault) cannot be maintained. Similar behaviour can also be found in numerical relays and it is a very relay-specific characteristic.

To cater for sequential earth faults on two separate feeders fed from the same busbar, a special grading margin between feeder E/F and busbar E/F relay has been adopted. The special grading margin covers the following:

a. Operating time of feeder E/F relay
b. Two times CB interrupting time
c. Two times relay overshoot time
d. Relay and CT errors for two feeder E/F relays and one busbar E/F relay under grading
e. Safety margin

Items (b) to (e) are similar to those in Section 4.2 except that items (b) and (c) are double and item (d) includes errors of two feeder E/F relays. Item (a) is added to the grading margin to cater for the additional feeder earth fault.

Similarly, the above special grading margin is also required for grading between BS (or BI) E/F relay and feeder E/F relay. The bigger grading margin will lead to longer fault clearance time for 11kV earth fault. However, it is considered a good compromise in view of the small earth fault current of less than 2kA and LV voltage dip less than 10%. Apart from the above cases, normal grading margin is applied to other E/F relays and to all O/C relays.

Fig. 5 shows typical grading curves for IDMTL relays.

Another note-worthy point is that according to our experience, the same type of relays having the same operating characteristic, especially the overshoot / reset characteristics, should be used at all points wherever possible, although this is not an absolute rule. If this practice cannot be followed, extra care is necessary to ensure that discrimination is maintained at all points.

5. Conclusion

Based on field experience of other utilities and ours, it can be concluded that the rough balance busbar protection has a number of advantages over the other types of busbar protection in our application. It is simple, cost effective and reliable that can serve our radial-feed distribution system well with single busbar configuration. However, for a more complex busbar configuration, it is not always possible to achieve the required grading margin using this scheme. For this reason, one should always consider its own unique network and operation characteristics in choosing the appropriate total protection solution for the distribution primary substation busbar protection which has direct impact to a large number of customers for any in-correct or mis-operation of busbar protection.

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References


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