

Enhanced Characteristics of Multi-Zone Current Differential Protection for Transmission Network

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1 INTRODUCTION

In general, distance relays are most appropriate for both local and remote backup protection since they require only local voltage and current measurements. However, as transmission lines and substations flourish, problems occur in the coordination and setting of distance relays. [1-2] stated that one of the major causes for cascading outage was the maloperation of backup protections employing the Zone-2 and Zone-3 distance elements. Adoption of communication systems can improve the sensitivity and selectivity of a distance relay. But it inevitably degrades one of the advantages of distance protection because it now requires remote data.

Unlike distance relays, current differential relays (CDRs) have a much better selectivity. Furthermore, with the introduction of GPS, all measured data can be time-tagged and compared to those at other terminals with minimum timing errors [3], thereby enabling the protection systems to cover a wider area. Hence, the GPS current differential protection is more suitable for wide area backup protection than distance protection in terms of communication requirement, selectivity and protection scale.

This paper proposes an innovative multi-zone differential protection (MDP) scheme for protecting wide area transmission networks. The term “multi-zone” indicates that this scheme covers more than one protection zone whilst “differential” suggests that current differential protection (CDP) algorithm is used. The MDP can serve as a backup protection system, or operate as a main-3 protection in Extra High Voltage transmission systems. It consists of distributed CDRs and these CDRs will interact with each other via high-speed communication networks. In normal situations where all data are available, the MDP is a collection of CDP schemes and each scheme operates individually. Whilst when the measurement data are missing from a particular end of a transmission line, the MDP does not block the related CDRs like conventional protection schemes. Conversely, the MDP can reconstruct the lost data and detect faults using the Representative Data (RD) technique. After the fault detection, the integrated Tripping Priority Strategy (TPS) can be deployed to minimize the outage area. Moreover, the MDP also provides a Terminal Exclusion Function (TEF) to check whether a fault still exists or a CB fails. Therefore, the MDP is more advantageous than conventional protection schemes (main or backup) since it can protect larger scale power system with high selectivity and at the same time solve the problem of data loss. The MDP may encourage development in the transmission network protection and greater use of WAN based protection and control concepts.

2 BASIS OF MULTI-ZONE DIFFERENTIAL PROTECTION

2.1 Scope of Multi-zone Differential Protection

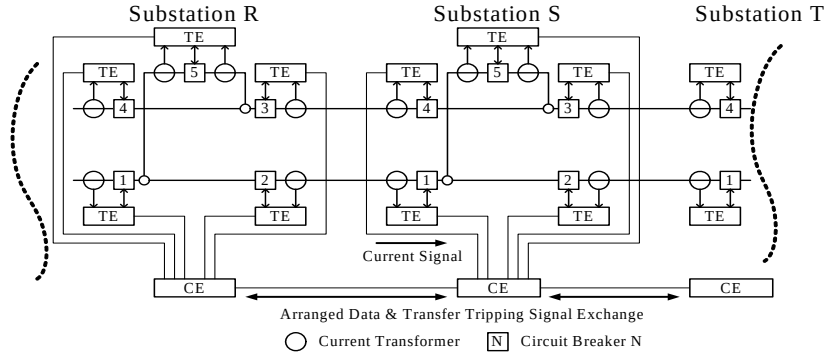


Figure 1: Overview of Multi-zone Differential Protection

The basic concept of MDP is shown in Figure 1 graphically. From Figure 1, TE represents the Terminal Equipment and it collects the measured values and CB status from the associated CT and CB respectively. Then the local CE (Central Equipment) collects data from each TE within the same substation. Besides, the local CE will receive measurement data from remote CE in the adjacent substation. Once the local CE obtains all data required for the CDP, it will make the protection decision (trip or block) and transfer the CB commands to local TEs and remote CEs.

Figure 2 indicates the scope of each CE. It is obvious that CE of Substation S (CE-S) covers the transmission lines R2-S1, R3-S4, S2-T1, S3-T4 and all the busbar section in Substation S. Therefore, CE-S can detect and clear any fault occurring in the grey area.

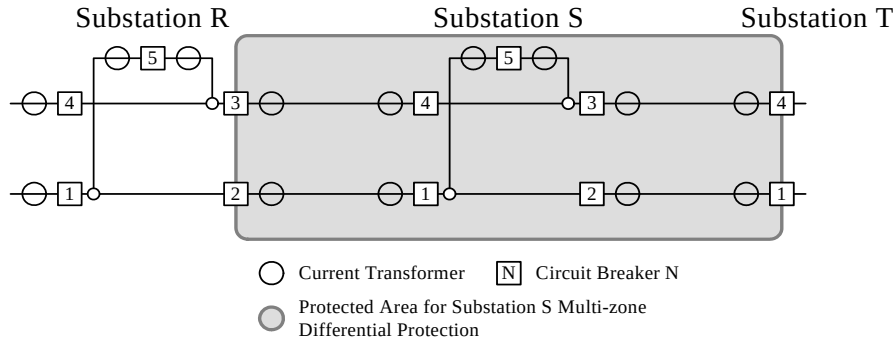


Figure 2: Scope of Central Equipment in Multi-zone Differential Protection

2.2 Local Backup Protection

From Figure 3, a fault F occurs on line R3-S4 and both main protections (CDP and distance protection) are assumed to be failed. Then CE-S gathers signals from TE-R3 (via CE-R) and TE-S4, detects the fault and tries to trip breaker CB-S4 first. A transfer trip signal will be sent to CE-R to open CB-R3. Simultaneously, CE-R tries to trip its breaker CB-R3 and sends a transfer trip back to CE-S to open CB-S4.

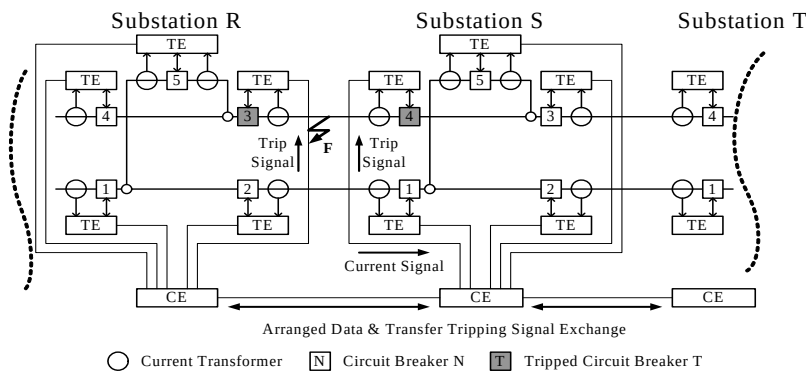


Figure 3: Local Backup Function of MDP

2.3 Breaker Failure Function

MDP uses the technique Terminal Exclusion Function proposed in [4] to initiate the breaker failure function. In principle, TEF assumes that the associated CB has opened successfully after a fault and then uses the remaining terminals and current differential algorithm to provide the breaker failure operation. In Figure 4, CB-S4 fails to open after the initial trip command and after a certain time delay, TEF assumes that CB-S4 and CB-R3 open successfully and they are excluded from the busbar protection S4-S5-S3 and busbar protection R4-R5-R3. Consequently, busbar protection S4-S5-S3 only receives data from terminal S5 and S3 and detects F as internal fault since .

Then CB-S5 and CB-S4 are tripped. While for busbar protection R4-R5-R3, as CB-R3 opens, .

As a result, CB-R4 and CB-R5 remain closed. In MDP, TEF is not only used for breaker failure function but also for coping with data missing problem.

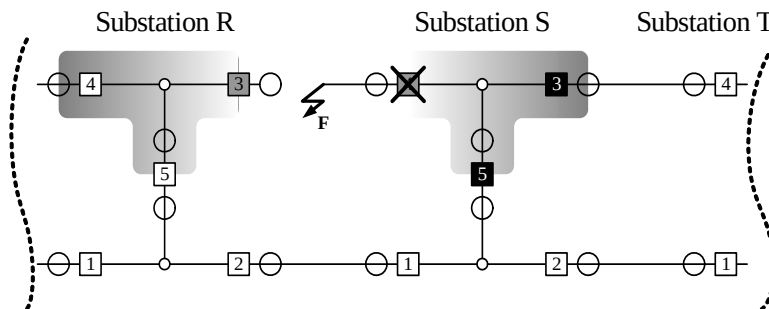


Figure 4: Breaker Failure Function of MDP

3 ENHANCED CHARACTERISTICS OF MULTI-ZONE DIFFERENTIAL PROTECTION

3.1 Loss of Data

In Part 1 of Figure 4, the TE failure refers to the situation where the acquisitioning function of TE does not operate correctly. This leads to the loss of data from that terminal and is considered as the main cause of data loss. Note: - when the tripping function of TE fails, it is treated as a breaker failure.

Part 2 represents the cable failure between CT and TE when the secondary signal from CT cannot be transferred to TE. Good commissioning and maintenance can reduce the probability.

The CT failure in Part 3 results in the same outcome as cable failure and again good commissioning and maintenance can limit the occurrence.

The communication network is composed of various devices such optical fibre, switch, network card etc and it is possible that one of them does not operate properly. For example, in Part 4 of Figure 4, a network hub can partially malfunction and data from some terminals may be lost. If the hub itself is out-of-service completely, the entire protection operation will be blocked. Hence, redundant network such as HSR/PRP is recommended in [5]: if one network fails completely, the traffic can be switched to the redundant network seamlessly.

3.2 Representative Data

The main idea of Representative Data (RD) is to use data from adjacent terminals to recover the missing data according to KCL. Terminals that will be used to reconstruct the lost data depend on the terminal position and the protection scheme considered. Different situations of RD based on the transmission network topology in Figure 5 are summarized in Table 1.

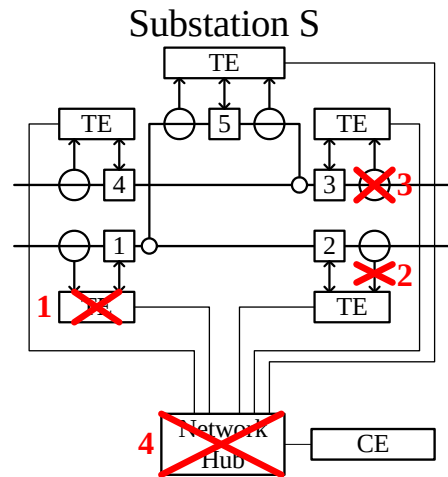


Figure 4: Failures in a Substation

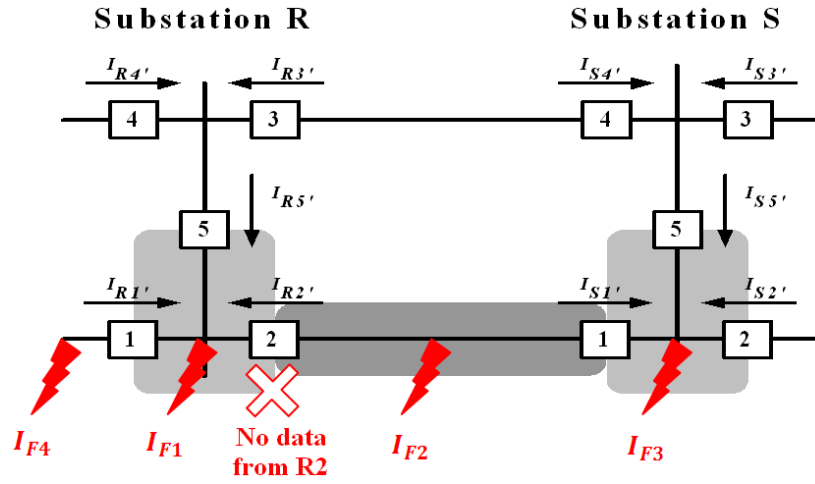


Figure 5: Protection Arrangement on a Double Circuit Transmission Network

Terminal with Data Lost	Protection Scheme Considered	Representative Data
R2 (joint terminal between line protection and busbar protection; similar to R1, R4, R3, S4, S3, S1, S2)	Line Protection R2-S1	$I_{R2}'' = -(I_{R1}' + I_{R5}')$; actual current at R2 is I_{R2}'
	Busbar Protection R1-R5-R2	$I_{R2}'' = -I_{S1}'$; actual current at R2 is I_{R2}'
R5 (terminal between double busbar; similar to S5)	Busbar Protection R1-R5-R2	$I_{R5}'' = I_{R4}' + I_{R3}'$; actual current at R5 is I_{R5}'

Table 1: Protection Arrangement on a Double Circuit Transmission Network

In Figure 5, data are lost at terminal R2 and both line protection R2-S1 and busbar protection R1-R5-R2 will use RD I_{R2}'' for CDP. More specifically, protection R2-S1 will compare I_{S1}' with I_{R2}'' whilst protection R1-R5-R2 compares $(I_{R1}' + I_{R5}')$ with I_{R2}'' . If the sum of I_{S1}' and I_{R2}'' or sum of $(I_{R1}' + I_{R5}')$ and I_{R2}'' is not zero, the differential current presents and the corresponding CDP operates.

(i) With respect to line protection R2-S1, the RD can be reconstructed as $I_{R2}'' = -(I_{R1}' + I_{R5}')$.

- ① For fault I_{F1} , $I_{S1}' = -I_{R2}'' = (I_{R1}' + I_{R5}' - I_{F1})$ and $I_{R2}'' = -(I_{R1}' + I_{R5}')$.

Hence, $I_{S1}' + I_{R2}'' \neq 0$ and the CDP R2-S1 would detect the differential current and operate for the external fault I_{F1} . Therefore, the outage area will be larger (CB-R1, CB-R2, CB-R5 and CB-S1 operate) compared to the normal operation for I_{F1} (CB-R1, CB-R2 and CB-R5 operate).

- ② For fault I_{F2} , $I_{S1}' = -(I_{R2}' + I_{F2})$ while $I_{R2}'' = -(I_{R1}' + I_{R5}') = I_{R2}'$.

So, $I_{S1}' + I_{R2}'' \neq 0$ and a certain differential current can be detected by CDP R2-S1. As a result, the CDP R2-S1 still operates correctly for its internal fault I_{F2} .

- ③ For fault I_{F3} , $I_{S1}' = -I_{R2}'$, $I_{R2}'' = -(I_{R1}' + I_{R5}') = I_{R2}'$.

Therefore, $I_{S1}' + I_{R2}'' = 0$ and there is no differential current for CDP R2-S1. So the unit protection R2-S1 will not operate for the external fault I_{F3} .

- ④ For fault I_{F4} , similarly $I_{S1}' = -I_{R2}'$, $I_{R2}'' = -(I_{R1}' + I_{R5}') = I_{R2}'$.

Then $I_{S1}' + I_{R2}'' = 0$ and CDP R2-S1 will remain stable for external fault I_{F4} .

(ii) From the viewpoint of busbar protection R1-R5-R2, the RD can be reconstructed as $I_{R2}'' = -I_{S1}'$.

- ① For fault I_{F1} , $(I_{R1}' + I_{R5}') = I_{F1} - I_{R2}'$ while $I_{R2}'' = -I_{S1}' = I_{R2}'$.

So $(I_{R1}' + I_{R5}') + I_{R2}'' \neq 0$ and CDP R1-R5-R2 would detect the differential current and operate for its internal fault I_{F1} .

- ② For fault I_{F2} , $(I_{R1}' + I_{R5}') = -I_{R2}'$ and $I_{R2}'' = -I_{S1}' = (I_{R2}' + I_{F2})$.
Then $(I_{R1}' + I_{R5}') + I_{R2}'' \neq 0$ and differential current will be detected by CDP R1-R5-R2.
So busbar protection R1-R5-R2 trips for the external fault I_{F2} , enlarging the outage area (CB-R1, CB-R2, CB-R5 and CB-S1 trip). In the normal case, only CB-R2 and CB-S1 trip.
- ③ For fault I_{F3} , $(I_{R1}' + I_{R5}') = -I_{R2}'$ and $I_{R2}'' = -I_{S1}' = I_{R2}'$.
Hence $(I_{R1}' + I_{R5}') + I_{R2}'' = 0$ and no differential current exists in the region R1-R5-R2.
So busbar protection R1-R5-R2 maintains closed for the external fault I_{F3} .
- ④ For fault I_{F4} , $(I_{R1}' + I_{R5}') = -I_{R2}'$ and $I_{R2}'' = -I_{S1}' = I_{R2}'$.
Consequently $(I_{R1}' + I_{R5}') + I_{R2}'' = 0$ and CDP R1-R5-R2 does not operate for the external fault I_{F4} .

In Figure 6, data from terminal R5 are not available and the busbar protection R1-R5-R2 and R4-R5-R3 are affected. Both of them will use RD I_{R5}'' for CDP. Due to symmetry, only CDP R1-R5-R2 is analyzed and it compares $(I_1(R1)'' + I_1(R2)'')$ with I_{R5}'' . If the sum of $(I_1(R1)'' + I_1(R2)'')$ is not zero, then differential current presents and CDP R1-R5-R2 operates.

With respect to busbar protection R1-R5-R2, the RD can be reconstructed as $I_{R5}'' = I_{R4}' + I_{R3}'$.

- ① For fault I_{F1} ,
 $(I_1(R1)'' + I_1(R2)'') = I_{F1} - I_1(R5)''$ and $I_{R5}'' = I_{R4}' + I_{R3}' = I_{R5}'$.
Therefore, $(I_{R1}' + I_{R2}') + I_{R5}'' \neq 0$ and CDP R1-R5-R2 would detect the differential current and operate for its internal fault I_{F1} .
- ② For fault I_{F5} ,
 $(I_1(R1)'' + I_1(R2)'') = -I_1(R5)'' = -(I_1(R4)'' + I_1(R3)'') - I_{F5}$
whilst $I_{R5}'' = I_{R4}' + I_{R3}'$. Hence, $(I_{R1}' + I_{R2}') + I_{R5}'' \neq 0$ and there is a differential current for busbar protection R1-R5-R2. It will operate for the external fault I_{F5} . As a result, the outage area will be larger (CB-R1, CB-R2, CB-R5, CB-R4 and CB-R3 trip) than that in normal situation where only CB-R4, CB-R5 and CB-R3 open.

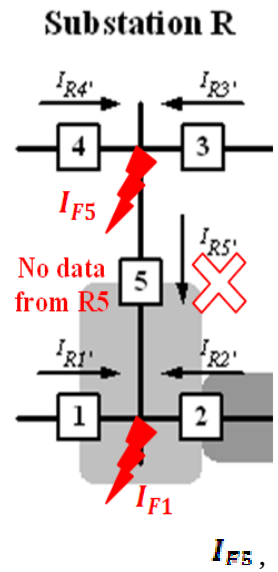


Figure 6: Protection Arrangement in Substation R

Although RD technique can be used to overcome the problem of data loss, it would extend the protection zone [6]. If the data loss occurs at the joint terminal between a line protection and a busbar protection (e.g. R2 in line protection R2-S1 and busbar protection R1-R5-R2), the protected area of line protection and busbar protection will be extended to cover both line and busbar. If the data loss happens at the joint terminal between 2 busbar protection schemes (e.g. R5 in busbar protection R1-R5-R2 and R4-R5-R3), the protection zone of both schemes will be extended to cover both busbars.

3.3 Tripping Priority Strategy

From the section above, the use of RD technique will extend the outage area if a fault is detected. In order to minimize this extended outage area, Tripping Priority Strategy (TPS) will be employed. The general algorithm of TPS differs depending on the position of terminals:

- For joint terminals between line protection and busbar protection (R1, R2, R4, R3, S1, S2, S4 and S3 in Figure 5), if data are lost at these terminals and faults (line faults or busbar faults) are detected via the RD technique, the associated CBs trip and their counterparts at the remote end of

the line protection should also trip. For example, when data are lost at terminal R2 and there is a fault in the extended zone R1-R5-R2-S1 in Figure 5, TPS will trip CB-R2 and CB-S1 immediately.

- For joint terminals between 2 busbar protections (R5 and S5 in Figure 5), if data are missing and faults (busbar faults) are detected via RD technique, only the corresponding CB operates while other CBs are blocked. For example, in Figure 6, if data are missing at terminal R5 and there is a fault in the zone R1-R5-R2-R4-R3, then CB-R5 will open immediately while CB-R1, CB-R2, CB-R4, CB-R3, CB-S1 and CB-S2 remain closed.

In Figure 7, data from terminal R2 are not available and the line fault I_{F2} and busbar fault I_{F1} are first detected using RD technique. TPS is applied after the fault detection. It is obvious that when I_{F2} occurs, TPS will trip CB-R2 and CB-S1 to clear I_{F2} immediately. However, in the case of busbar fault I_{F1} , it still exists after CB-R2 and CB-S1 operate.

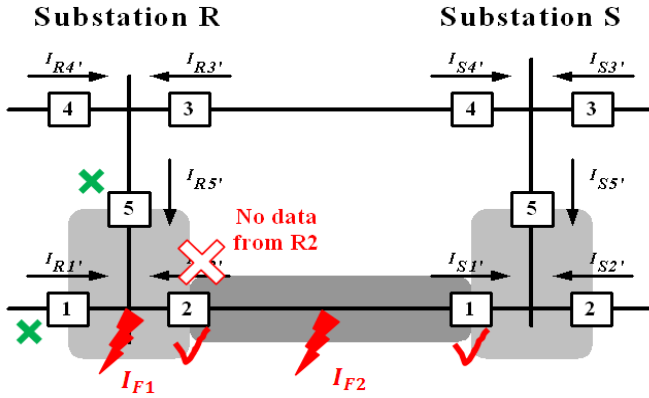


Figure 7: TPS for Joint Terminal R2 between Line Protection and Busbar Protection

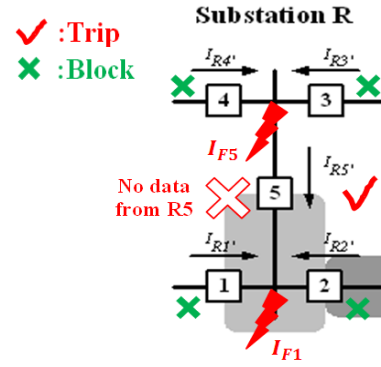


Figure 8: TPS for Joint Terminal R5 between Two Busbar Protections

Similarly, TPS cannot deal with busbar faults when data is lost from joint terminal between 2 busbar protections. In Figure 8, data are missing at terminal R5 and the busbar fault I_{F1} and I_{F5} can be detected by the RD technique. When TPS is used, only CB-R5 opens while the other breakers CB-R1, CB-R2, CB-R4 and CB-R3 are blocked. It can be observed that busbar fault I_{F1} and I_{F5} cannot be cleared after CB-R5 trips.

3.4 Terminal Exclusion Function

MDP provides a technique Terminal Exclusion Function (TEF) to overcome the issue that TPS cannot clear the busbar faults. Figure 9 shows the TEF for busbar fault when a joint terminal of line protection and busbar protection loses its data. After the application of RD and TPS techniques, only CB-R2 and CB-S1 trip whilst CB-R1 and CB-R5 are blocked. Then, TEF would assume CB-R2 has

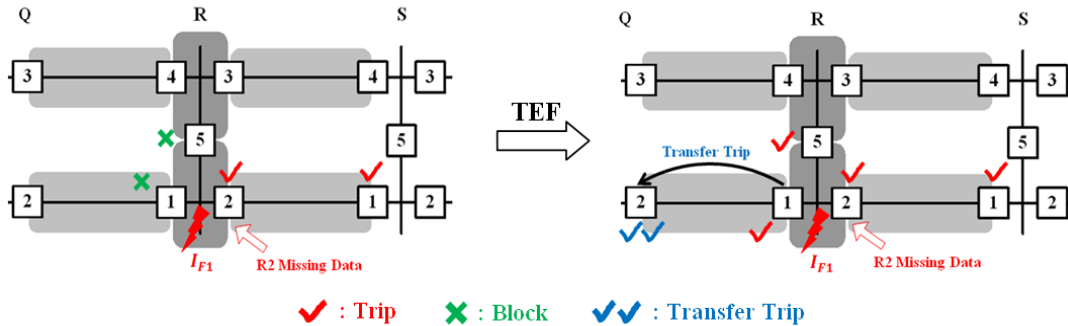


Figure 9: TEF for Busbar Fault when Terminal R2 Loses Data

already opened and terminal R2 will be excluded. Hence, $I_{R2}' = 0$ and TEF will only use I_{R1}' and I_{R5}' in the CDP algorithm. Since $I_{R1}' + I_{R5}' = I_{F1} \neq 0$, differential current exists for CDP R1-R5.

Consequently, CB-R1 and CB-R5 open, thereby clearing the busbar fault I_{F1} . At the same time, a transfer trip also arrives at terminal Q2 and CB-Q2 trips to de-energize the whole line Q2-R1.

Because of symmetry, only busbar protection R1-R5-R2 is considered. In Figure 10, when the joint terminal of 2 busbar protections – R5 loses data, RD and TPS only trips CB-R5 on detection of fault I_{F1} or I_{F5} . Identically, TEF assumes that CB-R5 has trip successfully and this leads to the judgement of $I_{R5} = 0$. CDP R1-R5-R2 only uses I_{R1} and I_{R2} to determine the existence of a differential current. For internal fault I_{F1} , as $I_{R1} + I_{R2} = I_{F1} \neq 0$, there is differential current in the zone R1-R5-R2. So CB-R1 and CB-R2 open to clear the fault I_{F1} . Transfer trip signals are also sent to Q1 and S1 to de-energize the line Q2-R1 and R2-S1. For external fault I_{F5} , because $I_{R1} + I_{R2} = 0$, there is no differential current in the region R1-R2. Hence CB-R1 and CB-R2 remain blocked and I_{F5} will be cleared by busbar protection R4-R5-R3 with TEF.

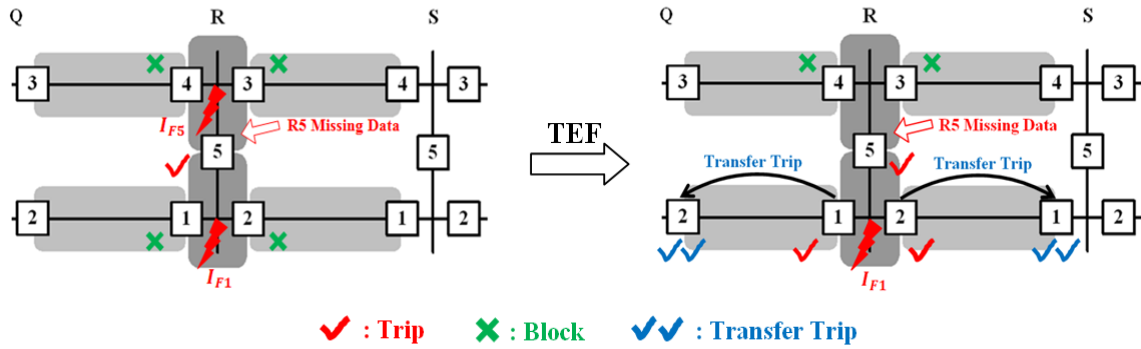


Figure 10: TEF for Busbar Fault when Terminal R5 Loses Data

3.5 Graph Theory and Representative Data

Graph Theory (GT) can be implemented in MDP to convert a power system network into a graph, which makes it easier to understand a complicated system. There are 3 procedures (Node Assignment, Branch Assignment and Direction Assignment) in GT and the following section describes how to convert a power network into a graph. Figure 11 shows the sample power network whilst Table 2 indicates the graph representation of components in the power system. In Figure 12, after Node Assignment, the lines, buses, substations and sections between CB and disconnector are transformed into nodes 1-12. Then, the Branch Assignment will connect these nodes via branches 1-17 in Figure 13. The Direction Assignment defines the directions of the branches. In this example, the local buses (node 5, 6) are assigned with the direction towards the sections between CB and disconnector (node 9 - 12). On the other hand, all sections between CB and disconnector (node 9 - 12) and remote substations (node 7, 8) point to the lines (node 1 - 4), which is demonstrated in Figure 14.

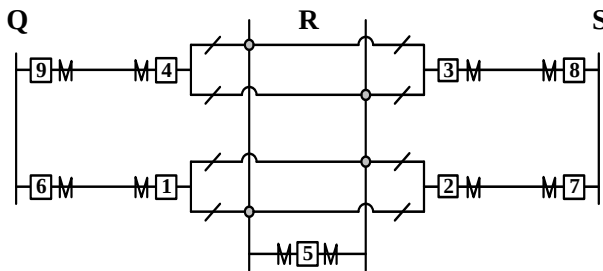


Figure 11: Sample Power System Network

Components in Power Network	Elements in Graph
Line	Node
Bus	Node
Remote Substation	Node
Section Between Breaker-CT And Disconnector	Node
Breaker-CT	Branch
Disconnector	Branch

Table 2: Graph Representation of Components in Sample Power System Network

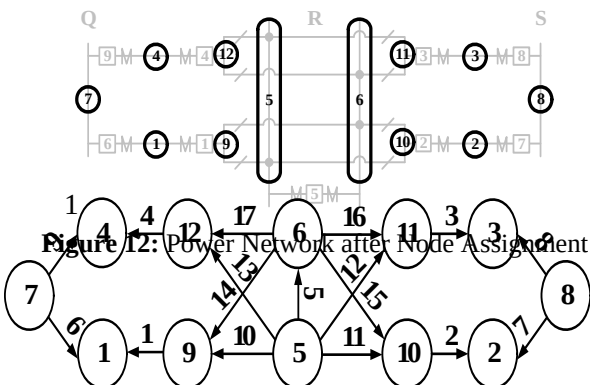


Figure 12: Power Network after Node Assignment

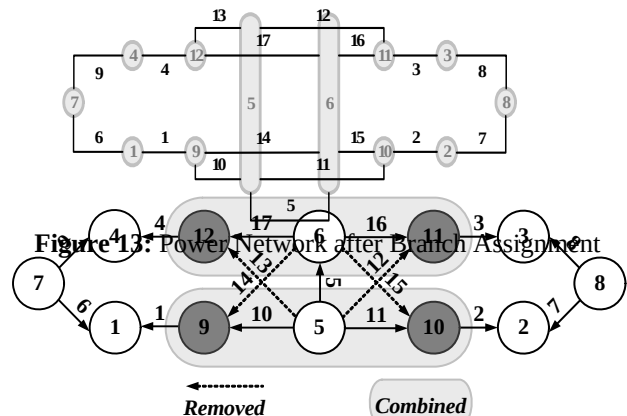


Figure 13: Power Network after Branch Assignment

Figure 14: Power Network after Direction Assignment

Figure 15: Branch Removal and Node Combination

To simplify the graph shown in Figure 14, Node Combination and Branch Removal are used. In the former, if the branches representing disconnectors are open (branch 12-15), they will be removed. In the latter, the nodes connected by the closed disconnector (branch 10, 11, 16, 17) will be combined. The procedures of Branch Removal and Node Combination are illustrated in Figure 15 while Figure 16 shows the simplified network graph. An Incidence Matrix can then be built based on the simplified graph and it is shown in Figure 18. In the matrix, the number of rows (N) represents the number of nodes while the number of columns (B) represents the number of branches. The value of each element is determined by the branch direction. For a branch “j”, it must link 2 nodes say “p” and “q”. If the direction of branch “j” is from node “p” to node “q”, then $(p, j) = -1$ while $(q, j) = 1$. The rest elements in column “j” are assigned with value 0.

N/B	1	2	3	4	5	6	7	8	9
1	1	0	0	0	0	1	0	0	0
2	0	1	0	0	0	0	1	0	0
3	0	0	1	0	0	0	0	1	0
4	0	0	0	1	0	0	0	0	1
5	-1	-1	-1	-1	1	0	0	0	0
6	0	0	-1	-1	1	0	0	0	0
7	0	0	0	0	0	-1	0	0	-1
8	0	0	0	0	0	0	-1	-1	0

Figure 17: Incidence Matrix based on Simplified Graph

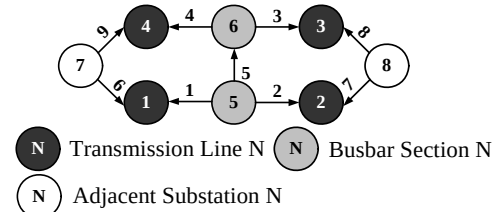


Figure 16: Simplified Power Network Graph

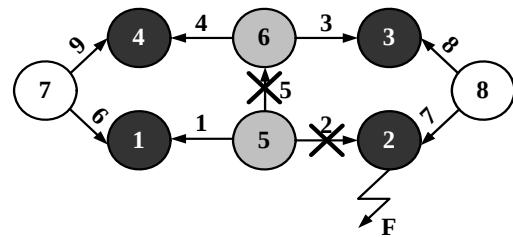


Figure 18: Data Loss at Branch 2 and Branch 5

The Incidence Matrix can be used to implement the RD technique. In Figure 18, data from branch 2 are missing and node 2 has to be protected, the RD technique searches for the element with either 1 or -1 , starting from column 2, row 2. When it finds row 5, the data in that row will be used to recover the missing data. In a worse case where data from branch 5 is also lost, the algorithm keeps searching and finds row 6. It then uses the data in row 6 to build the lost data. The process is shown in Figure 17.

4 CONCLUSION

The working principles of Representative Data, Tripping Priority Strategy and Terminal Exclusion Function have been described. With the employment of these algorithms, even when some of the data are not available, the Multi-zone Differential Protection (MDP) can still correctly operate as when data are complete. However, MDP significantly relies on the availability of high-accuracy time synchronization and high speed communication network. As a result, it would be necessary to investigate how to operate MDP properly if time synchronization and communication network are lost.

REFERENCES

- [1] J. C. Tan, P. A. Crossley, D. Kirschen, J. Goody, and J. A. Downes, "An expert system for the back-up protection of a transmission network," *IEEE Trans. Power Delivery*, Vol. 15, No. 2, pp. 508-14, Apr. 2000.
- [2] J. S. Thorp, A. G. Phadke, "Protecting power systems in the post-restructuring era," *IEEE Computer Applications in Power*, vol. 12, no. 1, pp. 33-7, Jan. 1999.
- [3] H. Y. Li, E. P. Southern, P. A. Crossley, S. Potts, S. D. A. Pickering, B. R. J. Caunce, and G. C. Weller, "A new type of differential feeder protection relay using the Global Positioning System for data synchronization," *IEEE Trans. Power Delivery*, vol. 12, no. 3, pp. 1090-9, Jul. 1997.
- [4] Y. Serizawa, H. Imamura, N. Sugaya, M. Hori, A. Takeuchi, M. Inukai, H. Sugiura, T. Kagami, "Experimental Examination of Wide-area Current Differential Backup Protection Employing Broadband Communications and Time Transfer Systems" 1999 IEEE Power Engineering Society Summer Meeting. Conference Proceedings. IEEE. Part vol. 2, pp. 1070-5, 1999.
- [5] C. De Dominicis, P. Ferrari, A. Flammini, S. Rinaldi and M. Quarantelli, "On the Use of IEEE 1588 in Existing IEC 61850-Based SASS: Current Behavior and Future Challenges" *IEEE Trans. Instrumentation and Measurement*, vol. 60, no.9, pp. 3070 – 3081, Sept. 2011.
- [6] K. Kangvansaichol, P. A. Crossley, "Multi-zone Differential Protection for Transmission Networks," 8th *IEE DPSP Conference, Amsterdam*, 2004.