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LOCAL DECISION MODULE FOR A MORE RELIABLE WIDE AREA PROTECTION SCHEME

Abdullah Ibrahim Al-Odienat and Khaled Al-Maitah

Electrical Engineering Department
Ahliyya Amman University
Amman 19328, Jordan
a.odienat@ammanu.edu.jo; kmaitah@outlook.com

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Abstract. *This paper proposes a new Wide Area Protection (WAP) scheme based on a combination between an adaptive directional over current protection and Local Decision Module (LDM) for an Active Distribution Network (ADN). The conventional adaptive protection is based on the communication between the WAP center and the protective relays. In case of any failure in the communication link, the protection system will fail. Using the proposed LDM, the protection system will operate properly through maintaining the coordination between the primary and backup protection relays in the whole system. The proposed scheme is designed to overcome the negative impact of distributed generations in ADN protection system. It also considers the case of communication failure between WAP center and protection relays in ADN. The proposed scheme proved its effectiveness in ADN. The proposed scheme has been modeled in MATALB and tested on a typical ADN. The simulation result proved the effectiveness of the proposed scheme, and its ability to deal with communication failure situation in ADN.*

Keywords: Power system protection, Adaptive protection, Directional over current relays, Local decision module, Active distribution network

1. **Introduction.** In recent years, the great development in renewable energy resources and increasing of electric power demand poses new challenges on the distribution networks [1]. The present Passive Distribution Networks (PDNs) are of dual structure as they consist of substations and loads [2]. Nowadays, there is a need to convert the current PDN into an Active Distribution Network (ADN) of a ternary structure: Distributed Generations (DGs), substations and loads [3].

The DGs have various benefits for the grid and customer such as voltage profile improvement, power loss reduction, increasing system capacity, reducing the outage frequency and duration and increasing the power quality and the system reliability [4]. On the other hand, the high penetration rate of DGs in distribution systems may lead to bidirectional power flow which may lead to a complication in protection coordination [5]. Therefore, the traditional existing protection system, in this case, will not satisfy the requirements of a reliable protection system due to the changes in the network topology [6].

To overcome the above problem, many researchers used adaptive protection schemes which mainly depend on changing the relay setting to match the new power system operating conditions [7]. In [8], for the proposed technique, the authors used an adaptive protection of three layers' architecture, the three layers are connected through communication media, and the management layer is the most important as it controls the overall

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protection system. However, if the communication link between the management layer and the other two layers is failed, then the entire protection system will fail.

In [9], the authors proposed a new protection scheme using a Smart Terminal Unit (STU). The proposed scheme is built based on the information exchange via the communication system to identify the faulted area and send out actuating signal to the corresponding devices to isolate fault. In their work, they assume that the STUs exchange logical information without synchronous sampling to reduce the requirements of the communication channel. Similarly, the authors in [10] used a logical information exchange to build a protection scheme. Since logical information is used, the size of information interaction will be small. However, their schemes are still unable to work with communication failure situation.

With the recent developments in communication technologies and smart grid facilities, many researchers started tackling the impacts of DGs on protection system of ADN based on the concept of Wide Area Protection (WAP). The WAP system is a part of wide area monitoring protection and control systems. The function of this system is mainly dependent on Phasor Measurement Units (PMUs) [6,10]. The PMUs measure the phasor values of current and voltage using a common time source for the synchronization of measurements [11].

[12] proposed a method to accomplish double-end fault location based on the synchronization characteristic of the PMU. The deployment of PMUs enhances the real-time monitoring and control of power system. However, the backbone of their scheme is the communication system.

[13] proposed an adaptive protection scheme for a micro-grid based on micro PMUs; the authors used the PMUs to estimate the system topology and the power contribution from each DG inside the micro-grid. [14] proposed the detection of fault location based on the comparison of the positive sequence voltage magnitudes at each bus of the network during the fault conditions; the authors used a Wide Area Monitoring System (WAMS) to estimate the voltage at each bus in the system. In [9], the authors took in consideration in their study the cost of PMU. They determined the optimal location of PMUs to build a Dynamic State Estimation (DSE).

Based on the previous literature review, and to the best of our knowledge, all of WAP schemes are mainly dependent on the communication link between the control center with the assumption that the communication link is safe. Practically, sometimes the communication media between control center and field device may fail.

In this paper, a new WAP scheme is proposed based on a combination between wide area adaptive protection strategy and local decision protection. The proposed scheme is designed to cover the case of communication failure between the control center and local field devices using Local Decision Module (LDM). The LDM is installed at each local area in the system, it gets a permission to work in case of communication failure. The LDM is based on a logical information exchange between field devices.

The organization of the rest of this paper is as follows. In Section 2, the proposed wide area scheme is described in detail including the mode of operation, optimum relay setting calculation, and the LDM operation strategy. In Section 3, simulation results and discussion are obtained for distribution medium voltage power system. Finally, the conclusions are presented in Section 4.

2. **The Proposed WAP Scheme.** Based on the adaptive protection and logical information exchange strategy of the wide area network technology, the proposed protection scheme ensures high level of reliability to locate and isolate the fault. The framework of the proposed scheme is shown in Figure 1. The proposed protection scheme is aimed at

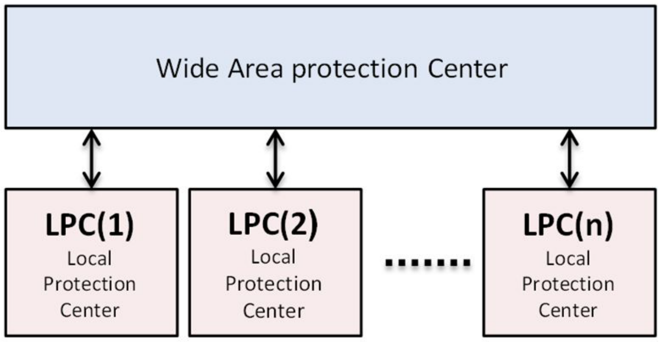

Figure 1. Framework of the proposed protection scheme

protecting the electrical equipment from the fault current by isolating the faulty section only.

The main philosophy of the proposed scheme is centered on dividing the distribution network into areas, and each area has one local protection center. All of the local protection centers are connected with a WAP center. As it is shown in Figure 1, the proposed scheme may be divided into Local Protection Centers (LPCs) and WAP center. The main component of LPC is the PMU which is responsible for providing the synchronized phasor measurements of the voltages and currents and the circuit breakers states at local level. All this information is then sent to the WAP center.

The WAP center receives the information from different LPCs. If any change occurs in the system topology, the fault current calculations will be changed accordingly. The WAP center then determines the optimal setting for each relay and sends it to a specific register in the LPC called the local relay setting register.

In Figure 2, the proposed WAP is connected with simply ADN. The ADN consists of two main feeders, and one DG is integrated at each feeder. Each feeder is protected by Circuit Breaker (CB) and direction over current Relay (R). The substation is connected with grid via power transformer. WAP center in the proposed scheme, as shown in Figure 2, consists of topology process module, measurement database, topology error detection module, fault current calculation module and protection setting calculation block. As the idea in the adaptive protection is based on system topology process, the topology error detection module makes sure that the information retrieved from the LPCs is correct. After obtaining accurate information about system topology the fault current can be recalculated using calculation module, then the optimal setting of the relay in each local area can be determined.

In the proposed scheme, an LDM is introduced in LPC, and this module gets permission to work only when the communication link between LPC and WAP CENTRE is failed. With this modification, the protection system is now more reliable, and the case of loss of communication with WAP center is now considered.

The LDM gets information about magnitude and direction of the current in a logical form from all relays in local level. In case of communication loss between LPC and WAP center, all over current relays will be automatically changed from standard inverse characteristic to a time finite over current characteristic. The LDM determines the fault location, sends a trip signal to some relays, and sends a block signal to others.

2.1. **The operation modes of the proposed scheme.** In the proposed scheme, there are two operation modes based on the state of communication between LPC and WAP center. If the communication link is in a good state, the protection system will operate in an adaptive mode; otherwise, the protection system will operate at local decision mode.

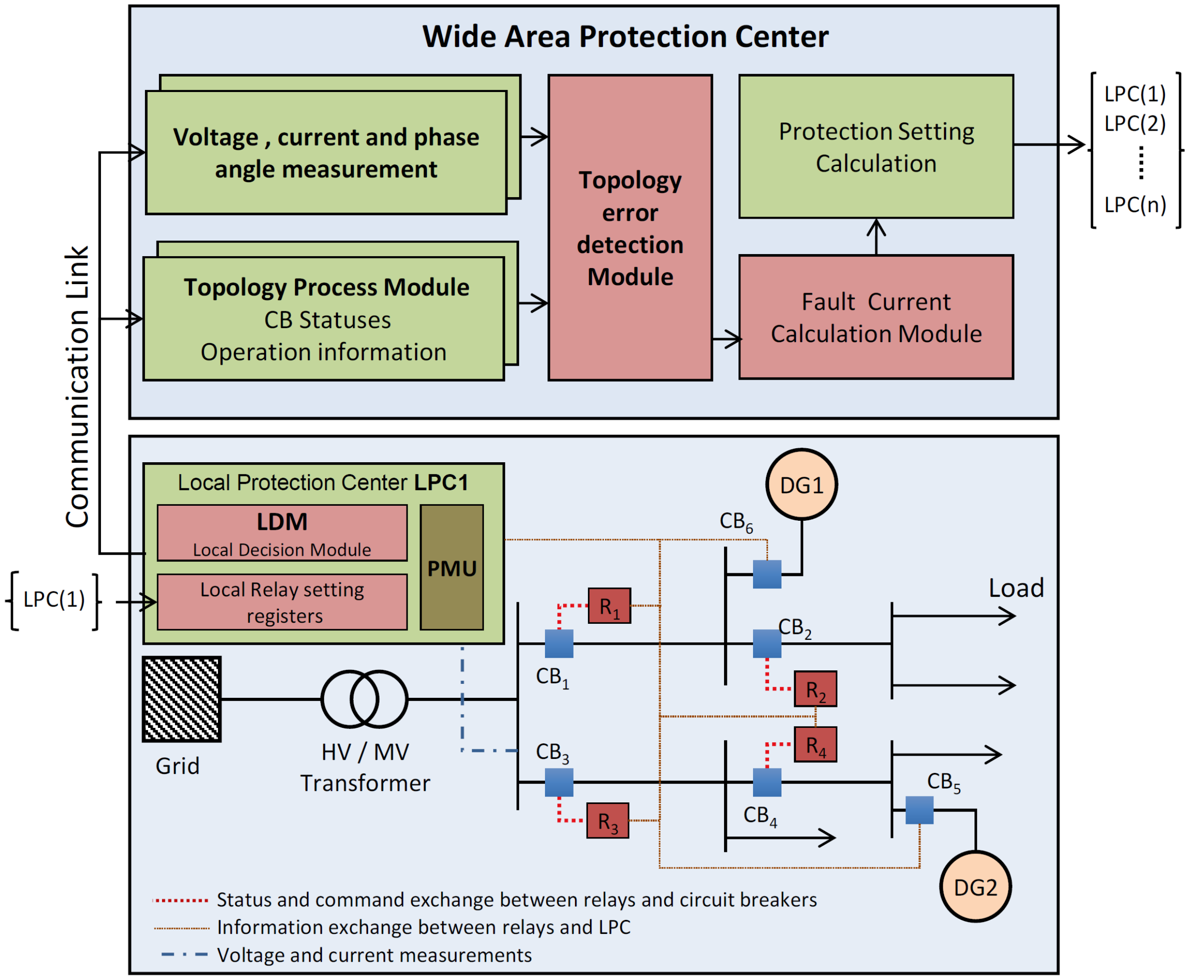

FIGURE 2. The proposed WAP scheme

In an adaptive protection mode, all relays in the local areas operate as standard inverse characteristic [14]. The relays setting updates to the optimal setting according to the topology change to prevent any miscoordination between primary and backup relays.

In the local decision mode, all of the local level relays which are not connected to WAP center, operate in a time finite over current mode. In this mode, the LDM receives the permission to determine the fault location and to send a trip and block signals to the relays according to the logical information.

2.2. **Optimal over current relay setting calculations.** When the protection system operates in adaptive mode, the optimal over current relay setting must be calculated. It is usually formulated as a constrained optimization problem. Several alternative objective functions have been proposed in [15,16]. The most common objective function used in literature is the minimization of the sum of the operating times of all the directional over current relays for the maximum fault current, and this objective function is expressed as follows:

$$OF = \sum_{i=1}^{m} t_{op,i} \tag{1}$$

where m is the number of relays in the local area, and $t_{op,i}$ is the operation time for relay R_i. The operation time for relay R_i can be calculated by

$$t_{op,i} = \frac{\mu \cdot TMS_i}{(I_{F,i}/PS_i)^{\beta} - 1} \tag{2}$$

where TMS_i is the time multiple setting for Relay R_i, and $I_{F,i}$ is the maximum current flows through relay R_i. PS_i is the relay plug setting. μ and β are the relay characteristic constants as shown in Table 1.

TABLE 1. Over current relay constant

Relay type	μ	β
Standard inverse relays	0.14	0.02
Very inverse relays	13.5	1
Extremely inverse relays	80	2

Practically, the objective function (1) minimizes the operating current only for primary relay without taking account of the backup relay operating time [17,18]. To minimize the operating times of the backup relays along with those of the primary relays, the objective function in (3) is used in our paper:

$$OF_{i,j} = \sum_{i=1}^{m} (t_{op,i})^2 + \sum_{i=1}^{n} (t_{op,j} + MCT)^2 \tag{3}$$

where $OF_{i,j}$ is the summation of operating times for the primary relay R_i and the backup relay R_j. $t_{op,i}$, $t_{op,j}$ are the operating time of the primary relay R_i and backup relay R_j, respectively. MCT is the Minimum Coordination Time between primary and backup relays. The objective function (3) is subjected to the following constraints:

1) If a primary relay R_i has a backup relay R_j for a fault at any line k, then the coordination constraint is expressed as follows:

$$t_{op,j} - t_{op,i} \geq MCT \tag{4}$$

where $t_{op,i}$, $t_{op,j}$ are the operating time for the primary and backup relays, respectively.

2) The operating time for the relay R_i should be larger than the minimum operating time and less than the maximum operating time, and this constraint can be expressed as:

$$t_{i,\min} \leq t_{op,i} \leq t_{i,\max} \tag{5}$$

where $t_{i,\min}$, $t_{i,\max}$ is the minimum and maximum operating time of the relay R_i.

3) The TMS and PS should be within relay range:

$$TMS_{i,\min} \leq TMS_i \leq TMS_{i,\max} \tag{6}$$

$$PS_{i,\min} \leq PS_i \leq PS_{i,\max} \tag{7}$$

where $TMS_{i,\max}$, $TMS_{i,\min}$ are the minimum and maximum limits of the time multiple setting, respectively. $PS_{i,\min}$, $PS_{i,\max}$ are the minimum and maximum limits of plug setting, respectively. For numerical/digital type of relays, TMS and PS can have any continuous value within their ranges. For static or electromechanical relays, TMS can be any continuous value but PS can only have certain fixed discrete value within their respective ranges.

Based on [10], in this study the $PS_{i,\min}$ has been taken as the maximum of 1.25 time of the maximum load current and 1/3 time of minimum fault current. $PS_{i,\max}$ has been taken as 2/3 time of the maximum fault current measured in the secondary side of the current transformer.

2.3. **Local decision module.** In the proposed scheme, an LDM is added in the LPC, and this module gets permission to work only when the communication link between LPC and WAP center is failed. The LDM uses logical information obtained from the relays. It is assumed, in our study, that all relays can provide the current amplitude and direction in real time to the LDM in a logical form. To illustrate this idea, Figure 3 presents a typical distribution system with two feeders of two relays for each. R_1 is a backup protection for relays R_2 and R_4. R_2 is a backup protection for relay R_3. Similarly, relay R_4 is a backup protection for R_5. All relays send logic signals for the current amplitude and direction to the LDM. Each relay has two variable information: the first one is A_i denoted to the fault current amplitude and the second one is D_i denoted to the current direction of the relay. To explain the idea, a fault is assumed at point F1 in Figure 3. The fault current will flow from the grid to bus1; another fault current will flow from bus5 to bus1 driven by DG2. Then, the variable A_4 will be logically "1" which means that the fault current passed through R_4, but D_4 will be logically "0", which means that the direction of the fault current is negative. Applying a logic operation "AND", A_4 and D_4 will be AD_4 equal to logically "0". The output AD_4 will be transmitted to the LDM. It will produce a blocking signal to relay R_4. Similarly, AD_5 will be logically "0".

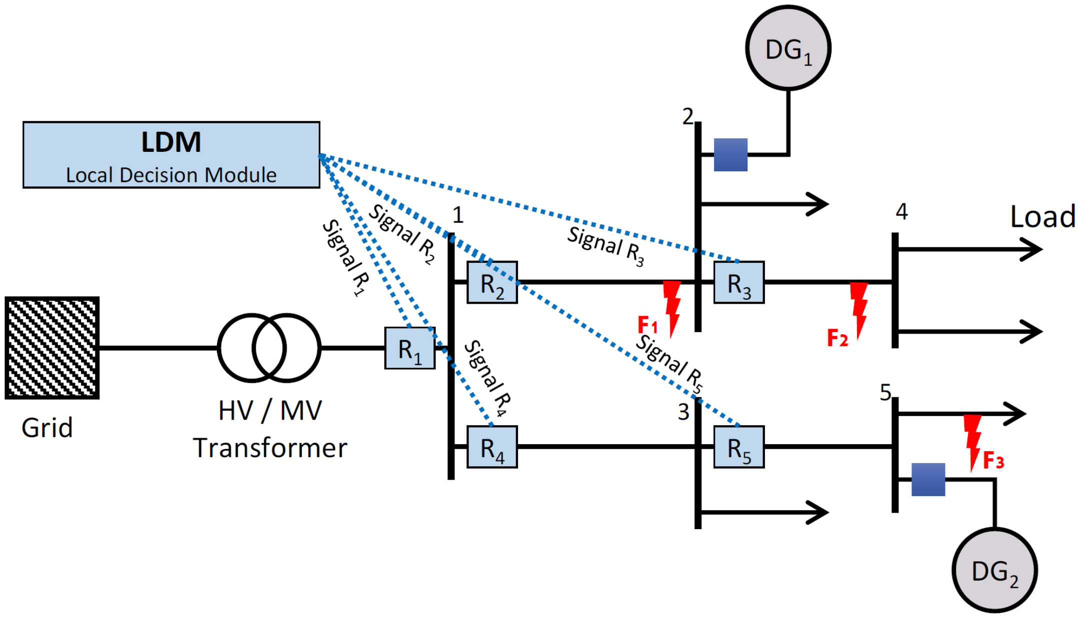

FIGURE 3. Typical distribution system

For the relays R_1 and R_2, AD_1 and AD_2 will be logically "1". However, for proper coordination between R_1 and R_2, the LDM starts from the upstream relay R_1. If AD_1 = "1" then the LDM needs to access the downstream relays R_4, R_2. However, as AD_4 = "0" and AD_2 = "1" for the fault location in feeder 1, the LDM needs to access the downstream relay R_3 which has AD_3 = "0", hence, the LDM will specify fault location between bus1 and bus2. Finally, the LDM will produce a trip signal to R_2 and R_1 with time delay of 0.2 and 0.4 seconds, respectively. The output signals for the faults F1, F2 and F3 are given in Tables 2, 3 and 4, respectively.

Based on the above decision, the LDM receives a logical data from all relays within the local area and produces blocking signals for all relays which are placed in non-faulted lines and sends tripping signals with time delay for relays which are placed within the faulted line. The flow diagram for the proposed LDM is given in Figure 4. Here, R_i is a backup protection relay for relay R_{i-1}, and R_{i-1} is a backup protection relay for R_{i-2}.

Table 2. LDM output signals for fault at F1

Relay serial number	A_i	D_i	AD_i (A_i AND D_i)	Trip signal	Delay time	Block signal
R_1	1	1	1	YES	0.4 sec	NO
R_2	1	1	1	YES	0.2 sec	NO
R_3	0	0	0	NO	–	YES
R_4	1	0	0	NO	–	YES
R_5	1	0	0	NO	–	YES

Table 3. LDM output signal for fault at F2

Relay serial number	A_i	D_i	AD_i (A_i AND D_i)	Trip signal	Delay time	Block signal
R_1	1	1	1	YES	0.6 sec	NO
R_2	1	1	1	YES	0.4 sec	NO
R_3	1	1	1	YES	0.2 sec	NO
R_4	1	0	0	NO	–	YES
R_5	1	0	0	NO	–	YES

Table 4. LDM output signal for fault at F3

Relay serial number	A_i	D_i	AD_i (A_i AND D_i)	Trip signal	Delay time	Block signal
R_1	1	1	1	YES	0.6 sec	NO
R_2	1	0	0	NO	–	YES
R_3	0	0	0	NO	–	YES
R_4	1	1	1	YES	0.4 sec	NO
R_5	1	1	1	YES	0.2 sec	NO

The coordination time between primary and backup protection has been chosen 0.2 second. The mathematical expression for the operating time for each relay produced by the proposed LDM is expressed as follows:

$$t_{op,i} = \sum_{m=i}^{i-n} (CT)(AD_m) \tag{8}$$

where $t_{op,i}$ is the operating time delay for relay R_i, n is the number of downstream cascaded relays with respect to R_i and CT is the Coordination Time. For example, the time delay for relay R_2 when a fault occurs at point F2 in Figure 3 is computed as in (9).

$$t_{op,2} = \sum_{m=2}^{2-1=1} (CT)(AD_m) = (0.2)(1) + (0.2)(1) = 0.4 \text{ sec} \tag{9}$$

In the LDM the transmission delay of real-time data can be controlled within 10 ms and the response time can be controlled in less than 100 ms. It fully meets the requirements of protection operation speed in distribution network.

3. **Result and Discussion.** To investigate the effectiveness of the proposed protection scheme, a simple real distribution system is chosen. The single line diagram of the chosen distribution system is shown in Figure 5. The system is of 4 buses and 4 lines. The system is connected to the grid at bus1. There are two 5 MVA DGs connected to the system

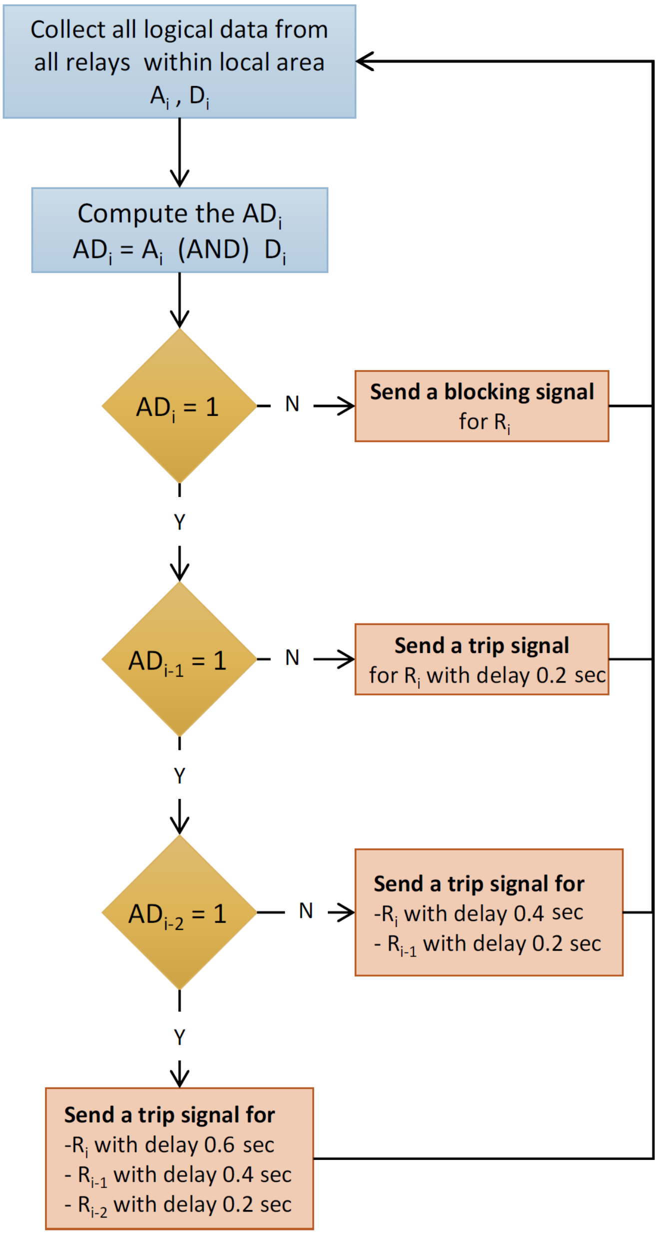

Figure 4. Flow diagram of the proposed LDM

at bus2 and bus4. The short-circuit rating of the grid is 250 MVA, while, the generators have a short-circuit rating of 25 MVA. The base voltage is taken as 11 kV and base MVA is 100. Each transmission line of the network has a resistance and reactance of 0.02 pu and 0.05 pu, respectively. In order to provide proper protection system, the system has 8 directional numerical over current relay and 2 relays at each line.

The Current Transformer (CT) for each relay is based on the maximum loading current and short circuit current. Table 5 proposes the selected CT ratio for all relays, the load current at peak load, the maximum and the minimum short circuit currents for each relay in the system.

3.1. **Scenario 1.** In the first scenario, the following assumptions are made.

1) DG2 is assumed to be isolated from the network.
2) Communication link with WAP center is at good state.

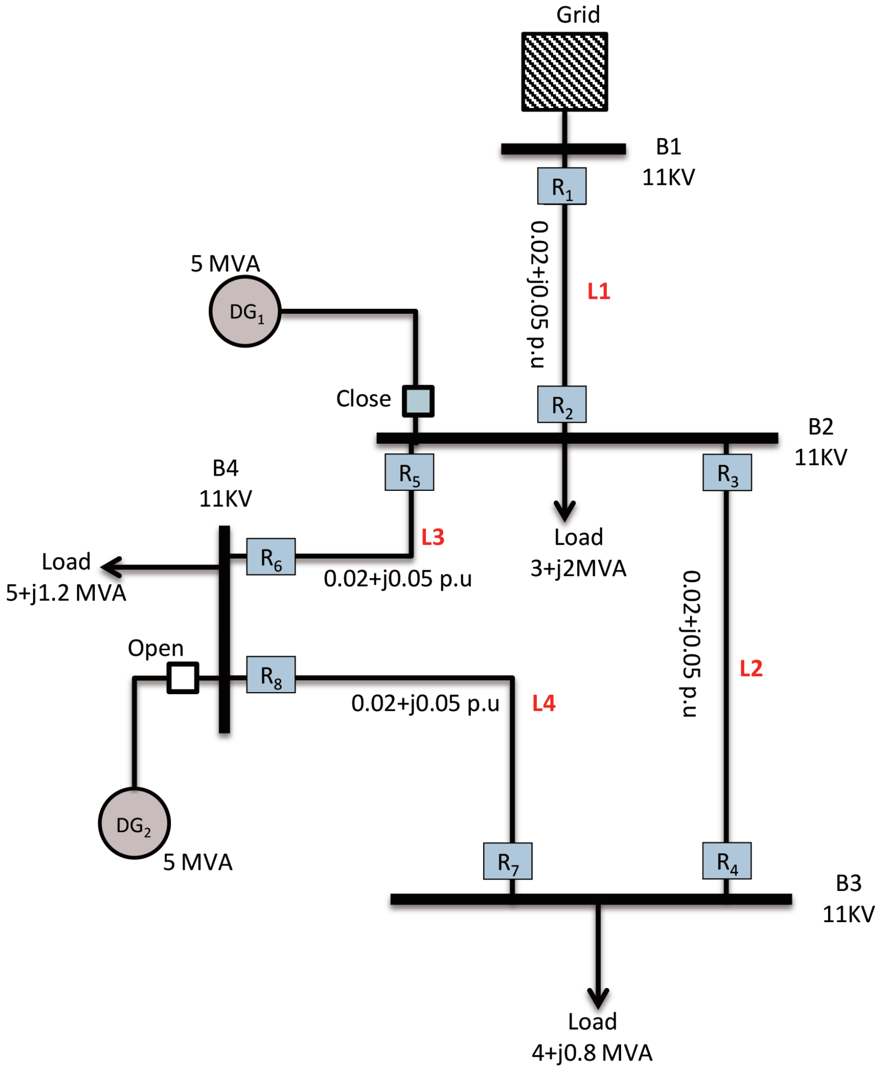

FIGURE 5. Distribution system under study

TABLE 5. Load current, fault current and CT ratio

Line No.	Relay No.	I_{load} (A)	$I_{f\ \min}$ (A)	$I_{f\ \max}$ (A)	CT ratio
L1	1	597	6543	8261	3000/5
	2	597	1701	2148	3000/5
L2	3	117	3412	4187	1200/5
	4	117	2271	2788	800/5
L3	5	178	3875	4735	1200/5
	6	178	1426	1742	1000/5
L4	7	62	3129	3810	1000/5
	8	62	1827	2225	600/5

According to the proposed protection scheme, the protection system will operate in adaptive mode, and all measurements and topology information will be sent to the WAP center to calculate the short circuit current in each line, in order to determine the suitable TMS and PS for all relays. Referring to Figure 5, there are 10 pairs of primary protection relays in the system. The short circuit current for each pair is given in Table 6.

TABLE 6. Short circuit current for primary and backup relays

Fault location	Pair No.	R_{prim}	R_{Back}	I_{prim} (A)	I_{Back} (A)
L1	1	2	4	2527	1542
	2	2	6	2527	821
L2	3	3	1	4466	4627
	4	3	6	4466	465
	5	4	8	3048	436
L3	6	5	1	4987	4481
	7	5	4	4987	384
	8	6	7	1989	1874
L4	9	7	3	4066	1587
	10	8	5	2491	2369

After obtaining the short circuit current for all relays, the optimal setting is generated from WAP system and sent to the relays. Figure 6 shows the PS and TMS setting for all relays. The maximum PS for relay No. 1 is 2, and the minimum PS for relay No. 7 is 0.6.

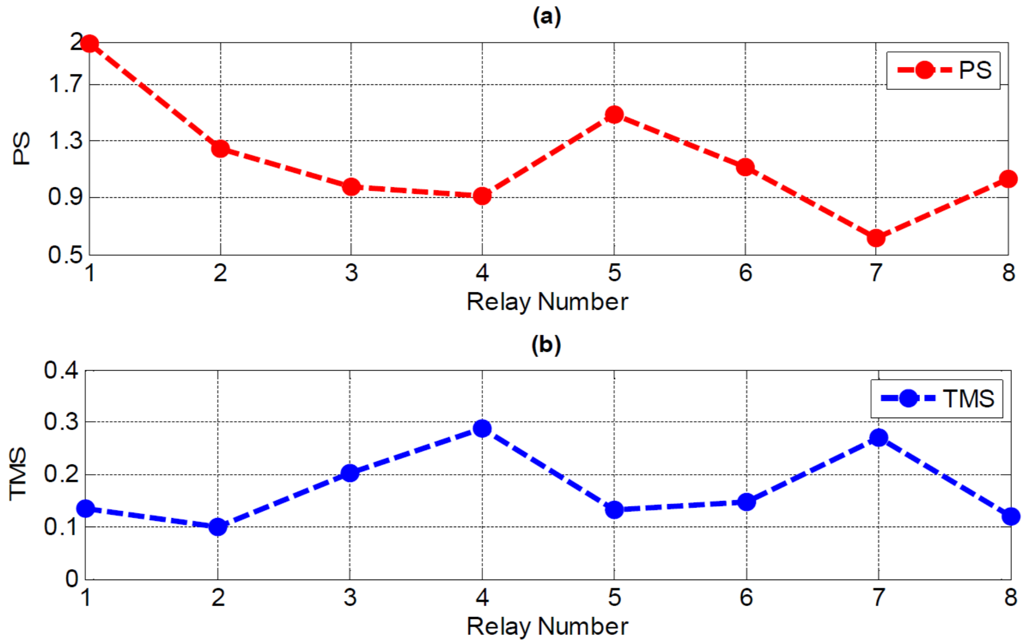

FIGURE 6. Relay setting from WAP center for all relays (a) Pluge setting PS (b) Time multiple setting TMS for all relays

To insure suitable setting for proper coordination between the primary and backup protection, the following calculations are carried out: (a) the operating time for all pairs of primary and backup relays, (b) the Coordination Time Interval (CTI) for all pairs and (c) the minimum acceptable coordination time MCT, as shown in Figure 7. For example, if a fault occurs at line L1, the primary protection is R_2 and the backup protection is R_4, pair No. 2 in Table 6. From Figure 7, it is clear that (a) the operating time of the primary protection (R_2) is about 0.5 seconds. The operating time for the backup protection (R_4) is about 0.7 seconds. The coordination time exactly equals 0.2 seconds. Similarly, the coordination time for pair No. 3 is about 0.22 seconds, and for pair No. 4 is about 0.9 seconds, and so on. So, there is no pair of primary and backup relay has a coordination interval less than 0.2 sec.

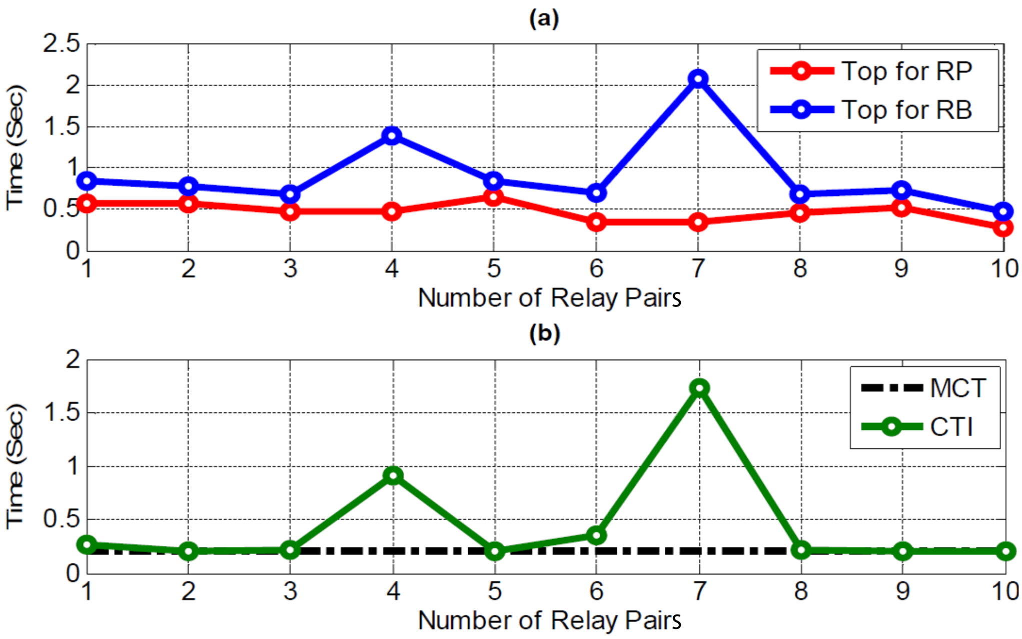

FIGURE 7. (a) Operating time in seconds for primary (RP) and backup (R-B) relays and (b) coordination time interval CTI and minimum coorination time MCT for all pairs of primary and backup relays

3.2. **Scenario 2.** In the second scenario, the effect of DGs on the proposed protection scheme is investigated. The following assumptions are made.

1) The DG2 is assumed to be integrated with network.

2) Communication link with WAP center is lost during the integration.

With integration of DG2 at bus 4 the short circuit must be recalculated. All measurements and topology information are sent to the WAP center to calculate the short circuit current for the entire network in order to determine the optimal relay setting to insure the proper coordination between primary and backup protection. The short circuit calculation is shown in Table 7. It is noted the short circuit current increased in some lines after DG integration.

The operating time for primary and backup protection pairs and the coordination time interval CTI are shown in Figure 8.

TABLE 7. Short circuit current after DG2 is integrated

Fault location	Pair No.	R_{prim}	R_{Back}	I_{prim} (A)	I_{Back} (A)
L1	1	2	4	3207	1693
	2	2	6	3207	1373
L2	3	3	1	4840	4523
	4	3	6	4840	465
	5	4	8	3382	919
L3	6	5	1	5074	4457
	7	5	4	5074	505
	8	6	7	2866	1595
L4	9	7	3	4091	1741
	10	8	5	3342	2111

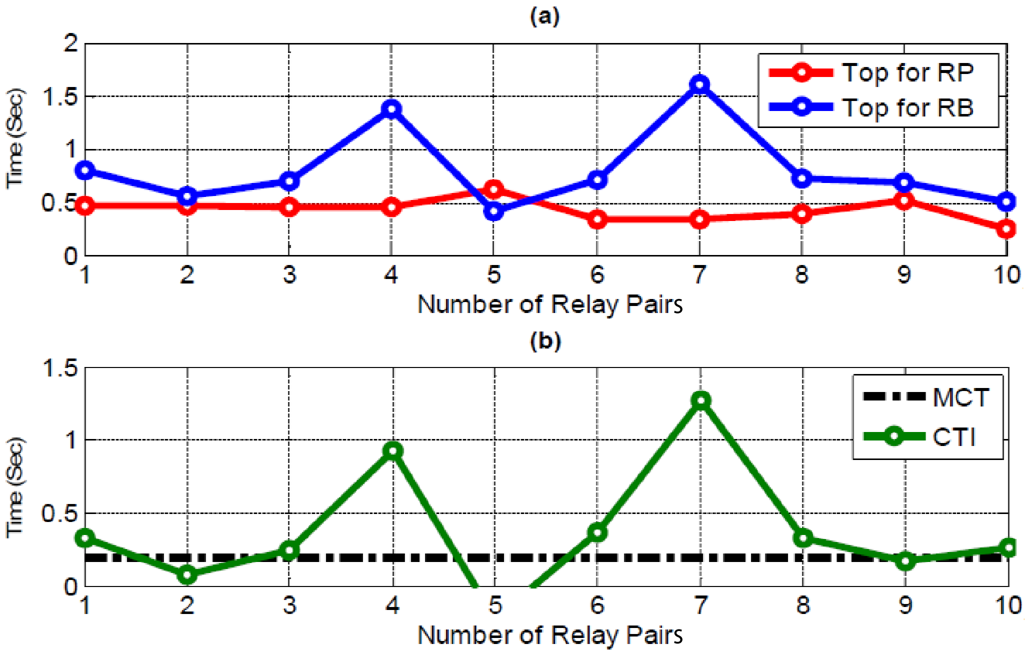

Figure 8. Communication link failure: (a) the operating time for all relay pairs after DG2 is integrated; (b) the coordination between primary and backup protection

Figure 8(b) clearly shows the coordination time is failed in pairs 2, 5, and 9, i.e., the coordination time between primary and backup protection relay is less than 0.2 seconds. According to the proposed scheme, the situation will be modified by LDM, as it gets permission to operate, immediately, when the communication link with WAP center is lost. The operating time of the primary and backup relay pairs according to the proposed scheme is shown in Figure 9.

As shown in Figure 9, the coordination between primary and backup protections is now proper, so the LDM has an effective contribution in the proposed scheme. All primary relays operate at 0.2 second and all backup relays operate at 0.4 seconds. This means that the coordination time is about 0.2 seconds. The LDM provides a good coordination solution when the communication link with the WAP center is lost.

In case, if the communication link is recovered, then the proposed protection scheme will operate as an adaptive protection and the setting for all relays will be generated in the WAP center after all measurements and topology information are received. Then the LDM returns to a sleep mode. Figure 10 shows the relay setting generated by WAP center after the DG2 is integrated and when the communication link is back to the service. It is clear that all relays have been properly optimized. Applying the short circuit current given in Table 7 for the new relays setting, the operating time for each relay can be obtained.

Figure 11 shows the operating time of the relay pairs after communication link is recovered. The optimal relay setting is determined by WAP center. Figure 11(b) clearly shows that there is no coordination time interval CTI less than MCT (0.2 sec). For example, the coordination time between the primary relay R_6 and the backup relay R_7 in pair No. 8 is about 0.27 seconds, and similarly between R_2 and R_6 is about 0.34 seconds.

According to the above discussion, the proposed scheme is successfully validated and can be recommended to be one of the modern and effective schemes to deal with communication failure between WAP center and the protection relays installed in the network.

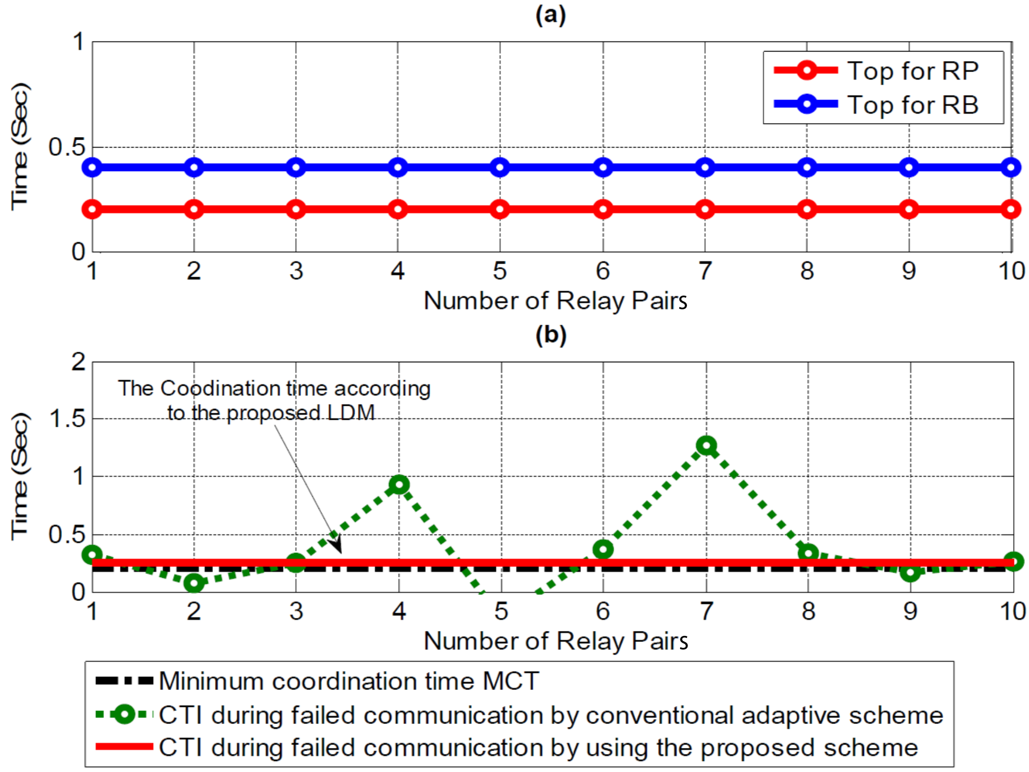

FIGURE 9. (a) The operation time for all pairs, and (b) the coordination time for all pairs, based on the proposed LDM scheme

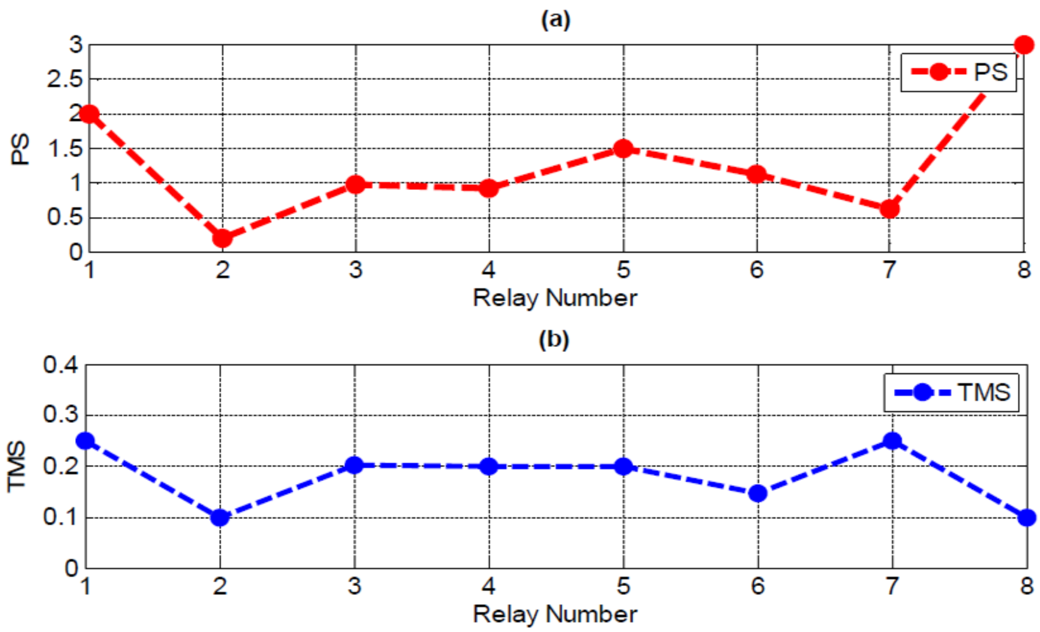

FIGURE 10. (a) Plug setting PS, and (b) TMS for all relays, by proposed scheme after the communication link return to the service

4. **Conclusion.** In this paper a new WAP scheme based on a combination between an adaptive protection and LDM is proposed. The proposed LDM gets permission to work only when the communication link with WAP center is lost, and it is designed to use logical information obtained from numerical relays installed in the system. The proposed

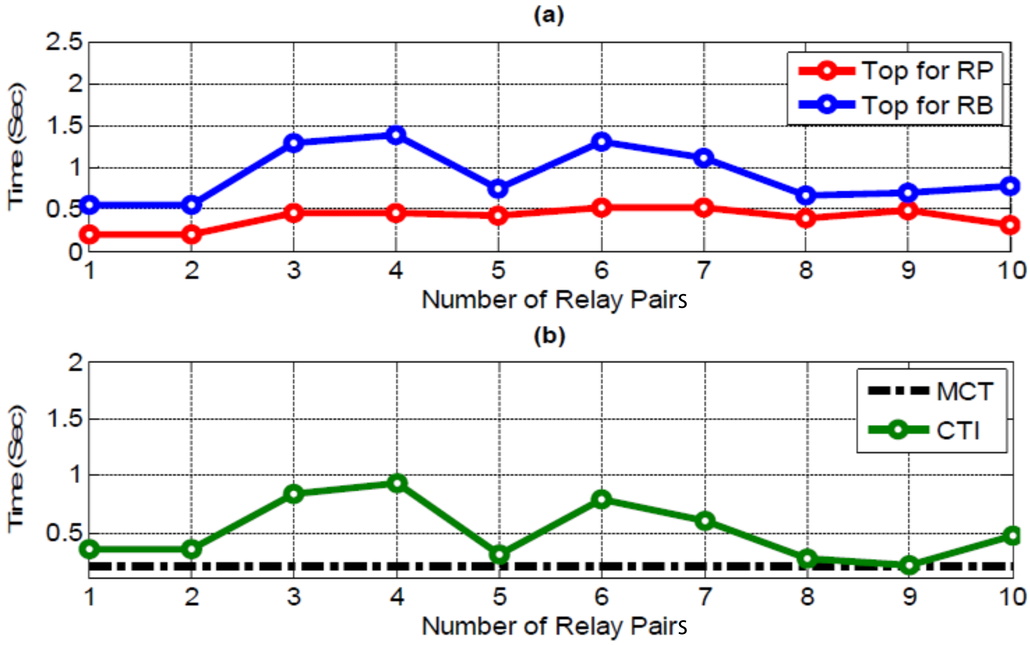

FIGURE 11. (a) Operating time relay pairs and (b) CTI and MCT for all for all relay pairs, by using optimal setting form the proposed scheme

scheme was planned to resolve the negative impact of DGs in the ADN protection system. The following benefits can be specifically concluded:

- The proposed protection scheme provides better relay setting under varying topology and generating conditions in the network.
- Mis-coordination situation due to the integration of DGs to the system can be dealt with by implementing the proposed protection scheme.
- The communication failure situation can be overcome by the proposed LDM.

The proposed scheme outperforms the existence WAP scheme in case of communication loss. Hence, the proposed scheme opens further scope for future work to WAP application with state estimation to deal with single PMU data loss of unreliable PMU data.

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