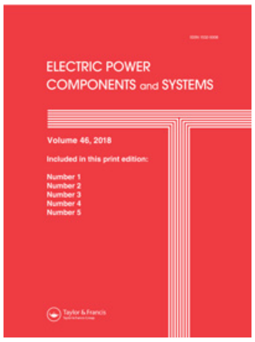

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A Decision-Tree Scheme for Responding to Uncertainties in Microgrid Protection Coordination

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CONTENTS

Abstract—In addition to the dynamic nature of microgrids, uncertainty in the proper operation of protection system and communication links are other challenges affecting the protection coordination of these networks. Therefore, in this paper, a new protection coordination plan based on decision tree for considering uncertainties in the topology of microgrid, protection system, and communication links is presented. The proposed method allows the adaptive protection to make global decisions and adopt the best strategy to clear faults depending on considered uncertainties. Since circuit breakers are the most prone to failure equipment in the protection system due to fault-caused stress, this paper models uncertainty in the protection system with uncertainty in the performance of circuit breakers. In order to consider uncertainty in circuit breakers and communication links, their probability of correct operation are not considered fixed but variable, respectively, proportional to the fault current flowing through the circuit breakers and the latency of communication links. The proposed plan was tested on a sample microgrid in DIgSILENT Power Factory. Results prove that using the proposed method, adaptive protection can establish an optimal sequence of strategies so that with the failure of each strategy, the best backup strategy is replaced given the uncertainties.

Keywords: microgrid, uncertainty, protection coordination, decision tree
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1. INTRODUCTION

Uncertainty in the microgrid topology, which is created due to its dynamic nature and the ability of microgrid performance in both normal and islanded modes, is a pivotal challenge of microgrid protection coordination [1]. In order to respond to uncertainty in microgrid topology, some studies have proposed adaptive protection [2].

Adaptive protection is an online activity that modifies the preferred protective response to a change in system conditions or requirements [3]. Reference [4] has categorized different methods which enable adaptive protection to respond to uncertainties of microgrid topology. Accordingly, references [3], [5], [6] have proposed offline adaptive protection. In order

NOMENCLATURE

CB	Circuit breaker
d_k	Length of the *k*th communication link
DG	Distributed generation
DP	Decision point
DP1	The first strategy of each layer of decision tree
DP2	Back up strategy that substitutes DP1 strategy
DT	Decision tree
I_{F_B}	Fault current flowing through *B*th CB
I_F^S	Fault current flowing through CBs in *S*th strategy
I_{R_B}	Rated current of *B*th CB
I_{U_B}	Upper failure threshold of *B*th CB
IN_{DP}	Evaluation index for optimal sequence of DP1–DP2 strategies
IN_{DP}^r	Evaluation index for DP1–DP2 strategies when DP1 strategy is failed due to defect in its *r*th component
IN_{LA}	Layer index
IN_{SA}	Evaluation index for optimal sequence of DP1–DP2s strategies for inclusion in the DT
L_{Loss}^{DP1}	Amount of load outage due to applying DP1 strategy
L_{Loss}^{DP2}	Amount of load outage due to applying DP2 strategy
L_{Loss}^{S}	Amount of load outage due to applying *S*th strategy
$Load_T$	Total amount of microgrid load
N_{CB}^S	All CBs involved in *S*th strategy
N_f	Number of failure factors of candidate strategy for DP1
N_P^S	All communication paths that the central server has access to all involved CBs of *S*th strategy
$P(j)$	Probability of point *j* in the table of the probability density function of latency of communication links
$P_B^{S_i}(I_{F_B}, t_{L_{Max}}^{S_i})$	Probability of correct operation of *B*th CB when the central server commands it from *i*th communication path of *S*th strategy
$P_{L_k}^{S_i}(t_{L_k}^{S_i})$	Probability of correct operation of *k*th communication link in *i*th communication path of *S*th strategy
$P_{Strategy}^{DP1}(I_F^{DP1}, t_{L_{Max}}^{DP1})$	Probability of correct operation of DP1 strategy
$P_{Strategy}^{DP2}(I_F^{DP2}, t_{L_{Max}}^{DP2})$	Probability of correct operation of DP2 strategy
$P_{Strategy}^{S}(I_F^{S}, t_{L_{Max}}^{S})$	Probability of correct operation of the *S*th strategy
t_{Apply}^S	Time of applying *S*th strategy
$t_{Apply}^{S_i}$	Time of applying *S*th strategy when the central server sends trip commands through *i*th communication path
$t_{L_k}^{S_i}$	Latency of *k*th communication link in *i*th communication path of *S*th strategy
$t_{L_{k-Standard}}$	Standard latency of *k*th communication link
$t_{L_{Max}}^S$	Maximum standard latency of communication links of *S*th strategy
$t_{L_{Max}}^{S_i}$	Maximum latency of communication links in *i*th communication path of *S*th strategy
$t_{L_{Max}}^z$	Maximum standard latency of communication links of *z*th strategy
$X_{L_{Standard}}^{S_i}$	The point number in the table of probability density function of latency of communication links which is associated with maximum latency of communication links in *i*th communication path of *S*th strategy
α	Weighting coefficient associated with the importance of load outage due to applying DP1 strategy
β	Weighting coefficient associated with the importance of load outage due to applying DP2 strategy
δ	Weighting coefficient of load outage index in identifying optimal sequence for DP1-DP2 strategies
η	Weighting coefficient of probability of correct operation of strategies in identifying optimal sequence for DP1–DP2 strategies
τ	Propagation latency

to consider uncertainty of microgrid topology in adaptive protection, the works presented in [7], [8] suggested calculation of protection coordination after each change in the network. With advent of high speed and reliable communication networks, microgrid adaptive protection plans were able to operate online with high selectivity [9]. On this basis, in the presented methods in [10]–[12], during fault, data is shared among protection systems and the best decision is made according to the shared data among the stored offline decisions.

Due to a large number of dynamic cases of microgrid and time-consuming calculations of protection coordination, it is complicated to do the protection coordination procedure after each change in microgrid topology. In addition, the performance of offline schemes has been challenged for two reasons [13], [14]. Firstly, this method requires a lot of free memory for all possible situation of microgird. Second problem is that, this method is unable to cover all dynamic changes of microgrid including connected or disconnected of DGs in normal and islanded operation modes.

Another challenge which threatens the reliability of adaptive protection schemes is uncertainty in protection system and communication links which are not considered in previous studies [4]. Uncertainty in protection system has a complicated nature. Generally, this uncertainty occurs during operation of protection system in faults. This means that there is a fault in the network but the protection system that must clear the fault is failed and is unable to do so. Thereby, it causes undesirable outage and reduces the reliability of the system [15]. On the other hand, secure operation of an adaptive protection system based on communication links is affected by speed, latency, and security of its communication system [16]. Thus, it is clear that each plan provided for microgrid protection coordination, without taking into account the uncertainties affecting the performance of protection system lacks credibility. Accordingly, adaptive protection coordination plans should be developed in a way that, by making global decisions, the sensitivity of this method to the considered uncertainties is reduced as much as possible [4].

This paper proposes DT as an appropriate method to meet uncertainties which affect the protection system. Uncertainties which are considered in proposed plan include uncertainty in microgrid topology, uncertainty in CBs operation, and uncertainty in communication links. Creating DT for protection coordination results an optimal sequence of strategies to clear faults so with failure of each strategy the best strategy is substituted. In addition, using DT, the proposed method ensures the lowest load outage, while clearing faults with the highest probability of correct operation of the protection system and communication links. For this purpose load outage and the probability of correct operation of the protection system and communication links for the determined strategy in the proposed method are compared to the other strategies that are able to clear the fault. In addition, these values for the selected strategy of the proposed method are compared to the proposed methods of previous studies. In order to implement the proposed method of this paper, a central server which is connected to CBs via communication links is used. CBs are placed at two ends of all lines and are responsible to perform commands received from the central server. Since CBs are the most prone to failure equipment in the protection system due to fault-caused stress, this paper models uncertainty in the protection system with uncertainty in the performance of CBs. In order to consider uncertainty in CBs and communication links, the probability of correct operation of them is not assumed to be constant and varies depending on the fault current flowing through CBs and the latency of communication links. The proposed plan of this paper is tested on a sample microgrid. Results prove that the presented method is able to appropriately respond to uncertainties using global decisions.

This paper is structured as follow: in the second part, problems of microgrid protection coordination in which uncertainties of protection system are not considered are analyzed. In the third part, the new method for creating protection coordination in microgrid considering uncertainties is presented. Afterward, in the fourth part, results of implementing proposed method on a sample microgrid are analyzed.

2. PROBLEM STATEMENT

The probability of correct operation of the protection system and communication links is not always constant. Thus, a constant reaction to establish protection coordination cannot be implemented. To illustrate this, we assume that the network in Figure 1 is protected by an adaptive protection system using offline settings which are stored in memory of R1–R6 directional over current relays.

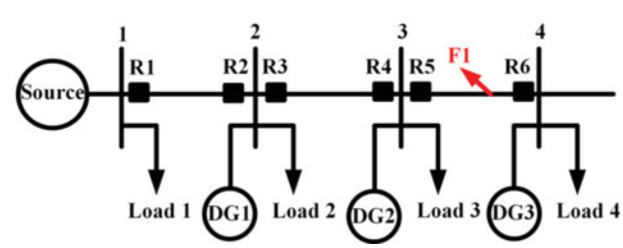

FIGURE 1. Sample network with local adaptive protection.

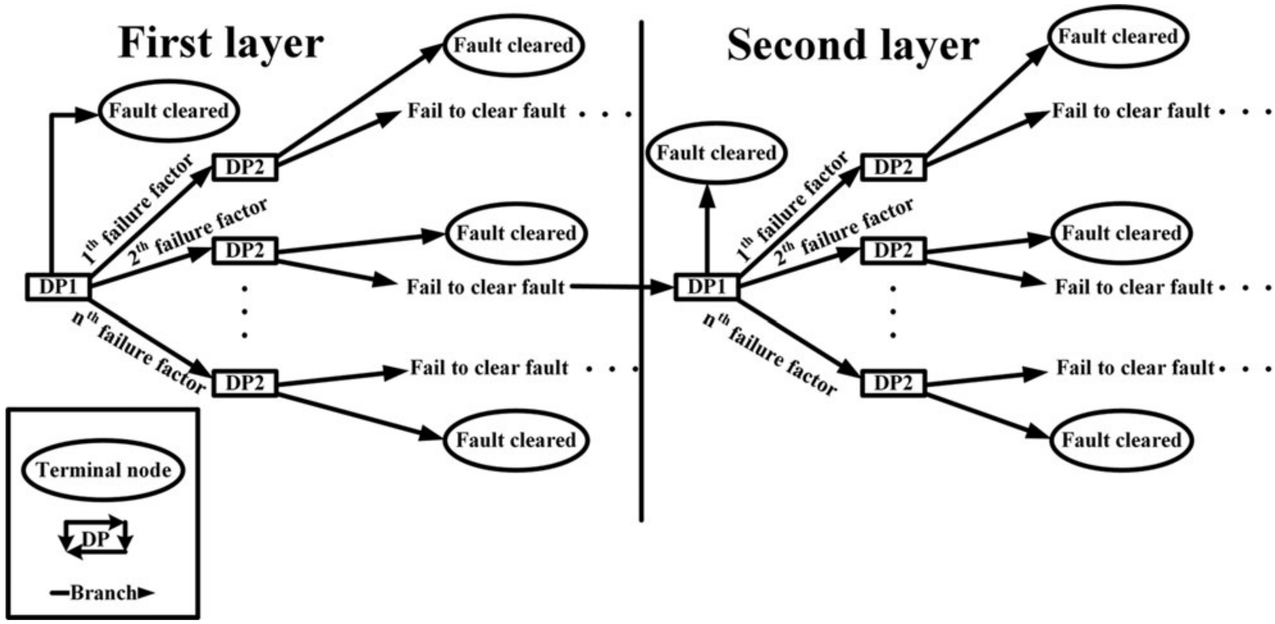

FIGURE 2. A sample DT.

If all DG resources were connected to the network and a fault occurred at the F1 point, according to traditional protection coordination schemes, both the protection systems at R5 and R6 should successfully operate to clear the fault. If the protection system R5 failed to clear the fault, it is expected that the protection system R3 clears the fault as the backup system. During time interval of clearing fault by the system R5, if the failure rate of CB3 was high, this system might fail and might not remove the fault. Therefore, fault remains in the network for a longer time and it can adversely affect other protection systems and cause cascading outages.

It is clear that in order to increase the reliability of the protection system, adaptive protection should be developed in a way that can make global decisions [4]. In this case, in addition to clearing fault with the minimum outage, the probability of the proper operation of protection system is also considered in the adoption of the best strategies to clear the fault.

3. PROPOSED METHOD

Traditionally, the strategy that is achieved by CBs of two ends of the faulted line is responsible for cleaning the fault. In order to move away from adopting the traditional decision-making by the central server, this server must review different strategies that are achieved using CBs that are far from the fault location and selects the best main and backup strategies, taking into account considered uncertainties.

In order to identify the best sequence of strategies to clear a fault, DT is proposed in this paper. DT is an efficient and strong tool for classification and decision making for high dimensional data spaces. DT is based on previous data of system and can be used for classifying new data [17]. It also can estimate the behavior of the system by using and analyzing a learning set.

DT has been suggested in [17]–[19] to detect faults in microgrids. But in this paper, it is used for providing protection coordination in microgrids. Figure 2 shows the optimal arrangement selected to apply strategies by the central server that led to a DT. According to this figure, DT is made of branches and nodes.

In the presented DT two kinds of nodes are considered. DPs are nodes which propose the best strategy for clearing a fault by analyzing input data which are the network topology and the probability of correct operation of protection system and communication links. On the other hand, terminal nodes are nodes that identify clearance of the fault and the end of DT procedure according to strategies that are implemented in DP nodes. Branches identify the next step of DT according to DPs output. If DP output was successful clearance of the fault, the tree is directed to a terminal node. If the fault was not cleared successfully, different branches, that are failure reasons of the DP strategy direct the tree to other DP.

According to Figure 2, the proposed DT is formed layer by layer. The best sequence of implementing strategies for clearing a fault in the first layer of DT is identified according to the network topology and the probability of correct operation of protection system and communication links. DP1 is the first strategy of each layer of DT for clearing a fault. If the fault was cleared by DP1 strategy, the DT would move to a terminal node and otherwise another strategy (DP2 strategy) is substituted according to the failure reason of DP1 strategy.

According to Figure 2, if DP1–DP2s specified in a layer of DT fail to successfully clear the fault from where these strategies have failed, other DP1–DP2s are determined to clear the fault. On this basis, another layer of DT is formed.

In order to form the proposed DT of this paper, different strategies that can clear the fault should be identified and the best sequence of strategies that can create DT be identified according to the considered indices.

3.1. Identifying Candidate Strategies for Clearing Fault

Since there are many strategies in order to clear a fault, strategies with higher protection coordination index should be candidate in order to limit them. On this basis, an index is presented in this paper which is combination of the traditional protection coordination index and the probability of correct operation of protection devices (CBs and communication links). This index is presented in Eq. (1). In this equation, the presented index is the proportion of load outage during implementing the associated strategy (p.u) to the strategy accuracy. As it is clear from Eq. (1), the accuracy of each strategy is not constant and depends on the amount of fault current flowing through CBs of that strategy and latency of communicating links of that strategy. It is obvious that among the strategies, the one with the least value of IN_{LA} index is selected.

To identify amount of usage of far strategies, in this paper, protective layer which are developed gradually are suggested. Different levels of protective layer are presented in Figure 3. According to this figure, in the first level of protective layer there are CBs in which the fault occurred in their protective line. The strategy of this layer is the traditional protection coordination strategy which is achieved by CBs of two ends of the faulted line. At the second level, the protective layer considers CBs neighboring the first-level CBs on both sides of the fault. Among all possible strategies established with the involvement of the second-level CBs, a strategy is selected that has the lowest IN_{LA} presented in Eq. (1). In the third level, the protective layer expands from both sides and considers the CBs connected to buses neighboring the second-level CBs. The strategy that is established with the involvement of the CBs of this level and its IN_{LA} is less than that of candidate strategy in the previous level is selected as the third-level candidate strategy. If there is such a strategy, it shows that getting away from the fault location and using farther strategies however increases the amount of outage by implementing candidate strategies but also increases the accuracy of the strategies. Accordingly, the protective layer expands and considers the CBs of the next level. The process of determining candidate strategies stops when none of the strategies of a level can create a IN_{LA} less than that of the previous level candidate. In this case, using farther strategies, however increase the amount of outage, cannot increase the accuracy of strategies compared to previous levels.

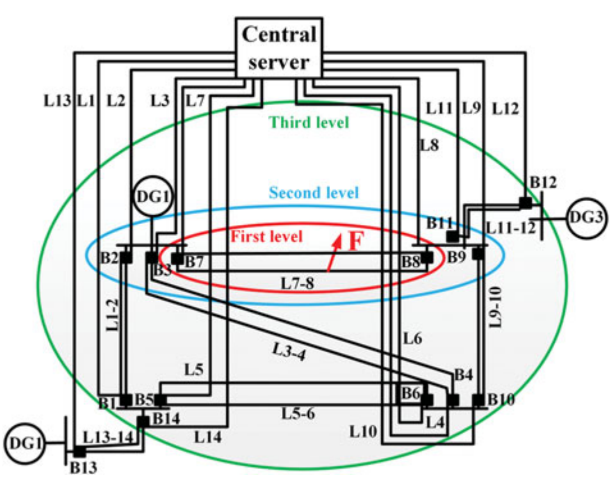

FIGURE 3. Central adaptive protection system with different protective layer levels.

$$IN_{LA} = \frac{L^S_{Loss}}{P^S_{Strategy}\ (I^S_F, t^S_{L_{Max}})} \tag{1}$$

According to Figure 3, central server connects to each CB through two communication links and sends trip commands to the associated CB through them. For instance, for the strategy that is achieved by B_7 and B_8 CBs, the central server sends trip commands through communication links of L_8 and $L_7 + L_{7-8}$ to the B_8 CB. If, for example the L_8 link failed to send the commands, but the communication link of $L_7 + L_{7-8}$ succeeded to send the commands, the communication has been successful. The communication system fails when the trip commands of the central server could not reach the engaged CBs from neither of communication links. In this case, the central server has to change the protection strategy and use other strategies. Thus, the proper operation of each strategy depends on the proper operation of all CBs involved in that strategy which receive appropriate commands sent by the central server from at least one communication path. Eq. (2) and Figure 4 are created on this basis.

$$P^S_{Strategy}\ (I^S_F, t^S_{L_{Max}}) = \sum_{i=1}^{N^S_P} \left(\prod_{B=1}^{N^S_{CB}} P^{S_i}_B \left(I_{F_B}, t^{S_i}_{L_{Max}} \right) \times \prod_{k=1}^{N^S_{CB}} P^{S_i}_{L_k} \left(t^{S_i}_{L_k} \right) \right) \tag{2}$$

According to Eqs. (1) and (2), the following steps should be considered in order to calculate the probability of each strategy.

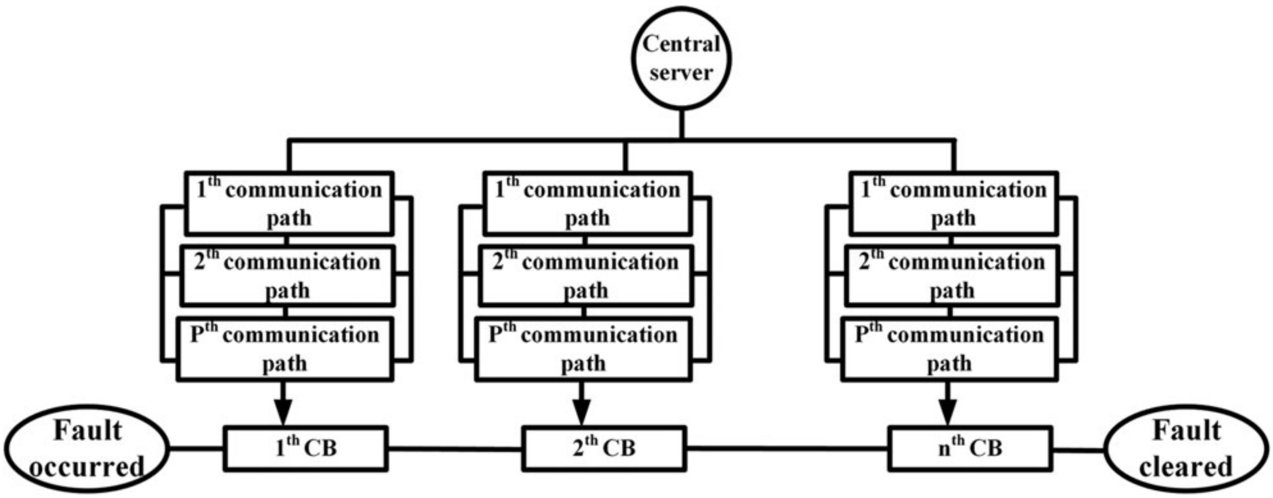

FIGURE 4. Logical relationship between equipment involved in each strategy.

(1) Identifying CBs engaged in each strategy.
(2) Identifying fault current flowing through CBs engaged in each strategy.
(3) Identifying communication links which can send the commands of central server to CBs engaged in each strategy.
(4) Calculating maximum time delay of communication links in each strategy.
(5) Calculating probability of correct operation of communication links engaged in the strategy according to their latency.
(6) Calculating probability of correct operation of CBs engaged in the strategy according to latency of their communication links and their fault current.
(7) Calculating the probability of correct operation of a strategy. This probability equals the probability of correct operation of all CBs engaged in the strategy and the probability of accuracy of operation of at least one of communication paths that connects the central server to each engaged CB.

3.2. Probability of Correct Operation of Communication Links

The probability of correct operation of communication links depends on their latency [20]. The standard latency of communication links depends on link type and its length and is obtained from Eq. (3) [21].

$$t_{L_{k-\text{Standard}}} = \tau\ (\text{ms/km}) \times d_k(\text{km}) \tag{3}$$

This should be noticed that in the presented plan, CBs of each strategy operate simultaneously during faults. Therefore, in each strategy, some links may have more latency than the standard defined latency. Excessive latency is the time that the command of the central server reaches to the CB which is located in the farthest distance to the server. This is also true for communication links involved in each path of the Sth strategy. For instance, in Figure 3, it is assumed that the protection strategy is operating of B_7 and B_8 CBs. On this basis, the central server for clearing the fault sends commands to these CBs via L_7 and L_8 communication links. If $d_7 > d_8$, then $t_{L_{7-\text{Standard}}} > t_{L_{8-\text{Standard}}}$. Since in the proposed plan it was assumed that CBs of different sides of fault operate simultaneously, in this strategy, the latency of L_8 communication link can be more than its standard value and equal to the maximum allowed latency of protection strategy ($t^S_{L_8} \le t_{L_{7-\text{Standard}}}$).

On this basis, in Eq. (2), what is considered as the probability of correct operation of communication links in ith communication path of Sth strategy is the probability of transferring data in a time less than the maximum standard latency of communication links in this path. Therefore, using the probability density function of [20], Eq. (4) is written for calculating the probability of correct operation of kth communication link in ith path of Sth strategy.

$$P^{S_i}_{L_k}\left(t^{S_i}_{L_k}\right) = P^{S_i}_{L_k}\left(t^{S_i}_{L_k} \le t^{S_i}_{L_{\text{Max}}}\right) = \sum_{j=1}^{X^{S_i}_{L_{S\tan dard}}} P(j) \tag{4}$$

3.3. Probability of Correct Operation of CBs

CBs can withstand the fault current for a limited time which depends on the magnitude of the fault current. Accordingly, the probability of correct operation of the CB is a function of its fault current passing through it and its duration [22],

[23]. Therefore, the probability of correct operation of CBs is obtained using Eq. (5) [22]. In this equation, the unit of all currents are (A) and the unit of $t^{S_i}_{Apply}$ is (s). The second line of Eq. (5) represents that the bigger the fault magnitude or the longer it lasts in the network, the probability of correct operation of CBs diminishes.

$$P^{S_i}_B(I_{F_B}, t^{S_i}_{L\text{Max}}) = \begin{cases} 1; & \text{if } I_{F_B} \leq I_{R_B} \\ 1-(I_{F_B}-I_{R_B}).t^{S_i}_{Apply}; & \text{if } I_{U_B} > I_{F_B} > I_{R_B} \\ 0; & \text{if } I_{F_B} \geq I_{U_B} \end{cases} \quad (5)$$

According to Eq. (5), if amount of fault current of Bth CB was less than I_{R_B}, this CB would certainly carry out the commands from central server correctly. In addition, if amount of fault current flowing through the CB was higher than I_{U_B}, this CB would certainly fail to operate. And if amount of fault current was between I_{R_B} and I_{U_B}, the probability of correct operation of this CB would be $0 < P^{S_i}_B(I_{F_B}, t^{S_i}_{L\text{Max}}) < 1$ [22].

According to Eq. (5), the time of applying the strategy ($t^{S_i}_{Apply}$) also affects probability of successful operation of CBs. The time of applying Sth strategy, is the time that the process of applying strategies reaches the point where Sth strategy is identified as the best strategy for clearing the fault. Therefore, to calculate applying time of Sth strategy, the time of passing through other strategies should also be mentioned.

The time of passing each strategy equals to the maximum latency of communication links of the associated strategy. As mentioned, commands are sent to the CBs via different paths. Therefore according to Eq. (6), the time of applying Sth strategy in its ith communication path equals to the maximum standard latency of communication links of the previous strategies plus the maximum standard latency of the active communication links in ith path of ith strategy.

$$t^{S_i}_{Apply} = t^{S_i}_{L\text{Max}} + \sum_{z=1}^{S-1} t^{z}_{L\text{Max}} \quad (6)$$

3.4. Identifying the Best DP1 and DP2 Strategies

Each DP1 candidate strategy may fail to clear the fault due to different reasons. On this basis, it is required that the best DP2 strategy be candidate for each DP1 candidate strategy (DP1–DP2). Therefore, for each failure state of DP1 candidate strategies, protective layer is formed and some strategies will be candidate for DP2 level. To identify the best DP1–DP2 sequence from candidate strategies, two factors are considered.

The first factor is that the fault is cleared with the highest probability of correct operation of protection system and the second is that during clearing the fault, the least possible amount of outage be occurred. Thus, according to the considered factors, using Eq. (7), the best DP2 strategy is determined for each of the failure causes of DP1 candidate strategies.

Equation (7) has two sentences. The first sentence illustrates the load outage which is caused by DP1-DP2 candidate strategies which is normalized with the total load of the microgrid. The second sentence in Eq. (7) represents the probability of correct operation of candidate DP1–DP2 strategies. In this sentence, it is assumed that either the fault is cleared by DP1 strategy with probability of $P^{DP1}_{Strategy}(I^{DP1}_F, t^{DP1}_{L\text{Max}})$ or if the DP1 strategy failed to clear the fault with the probability of $(1 - P^{DP1}_{Strategy}(I^{DP1}_F, t^{DP1}_{L\text{Max}}))$, the substitute strategy of DP2 clears the fault with the probability of $P^{DP2}_{Strategy}(I^{DP2}_F, t^{DP2}_{L\text{Max}})$. As mentioned before, the probability of correct operation of strategies is calculated according to fault current flowing through each engaged CBs and latency of associated communication links. Since the probability of correct operation of DP1–DP2 is desired to be more, this sentence is assumed to be reverse in Eq. (7) and besides the first sentence of this equation which shows the least possible outage caused by DP1–DP2 strategies, form IN_{DP} index. Therefore, it is clear that the DP1–DP2 arrangement which establishes the lowest IN_{DP} index is known as the optimal arrangement.

$$IN_{DP} = \delta\left(\frac{\alpha.L^{DP1}_{Loss} + \beta.L^{DP2}_{Loss}}{Load_T}\right) + \eta\left(\frac{1}{P^{DP1}_{Strategy}\left(I^{DP1}_F, t^{DP1}_{L\text{Max}}\right) + \left(1 - P^{DP1}_{Strategy}\left(I^{DP1}_F, t^{DP1}_{L\text{Max}}\right)\right) \times P^{DP2}_{Strategy}\left(I^{DP2}_F, t^{DP2}_{L\text{Max}}\right)}\right) \quad (7)$$

To determine the optimal arrangement of DP1–DP2s for inclusion in the DT, IN_{SA} is calculated according to Eq. (8).

$$IN_{SA} = \frac{1}{N_f}\sum_{r=1}^{N_f} IN^{r}_{DP} \quad (8)$$

In Eq. (8), the value of IN^r_{DP} for each DP1–DP2 composition is calculated using Eq. (7). According to Eq. (8), a composition of DP1 and its associated DP2s, which have the least value of IN_{SA} is decided as the optimal composition in the DT.

Thus, based on the aforementioned description, Figure 5 shows the implementation process of the proposed method. In subroutine 1 of this flowchart, DP1 and DP2 candidate strategies are determined and in subroutine 2 the probability of correct operation and load outage as the result of applying these

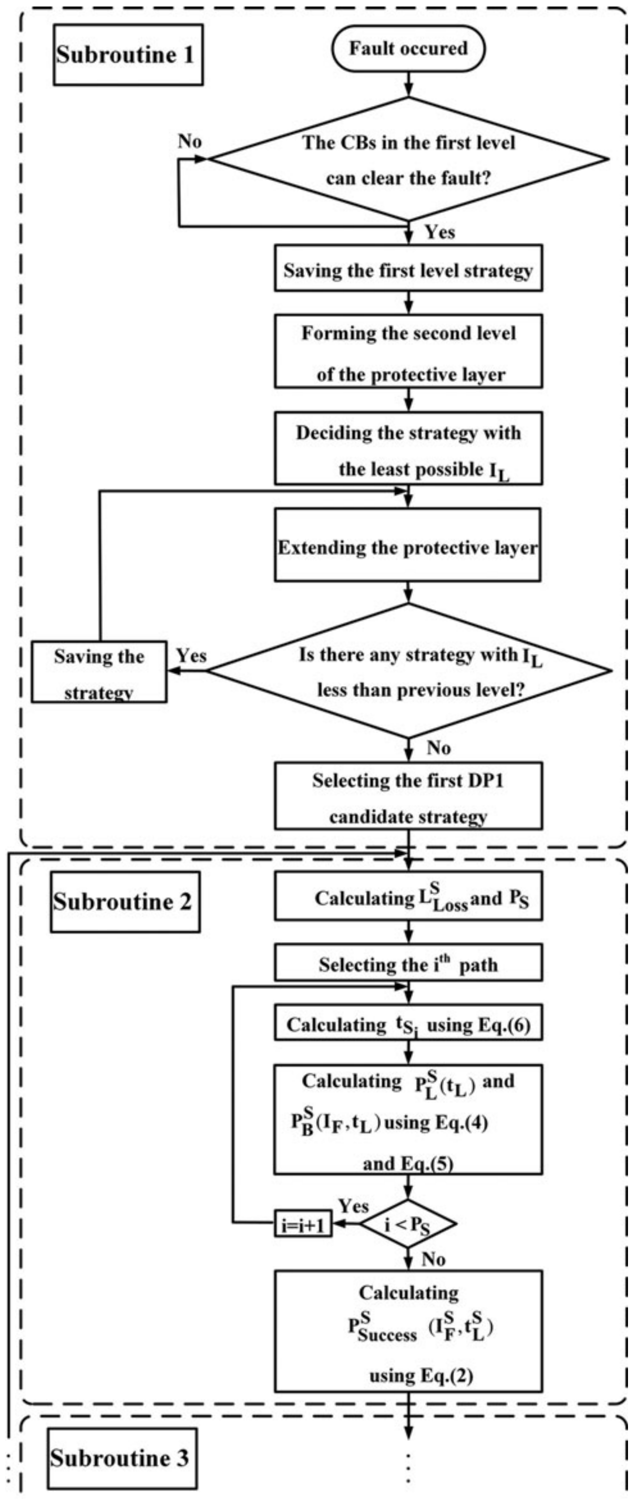

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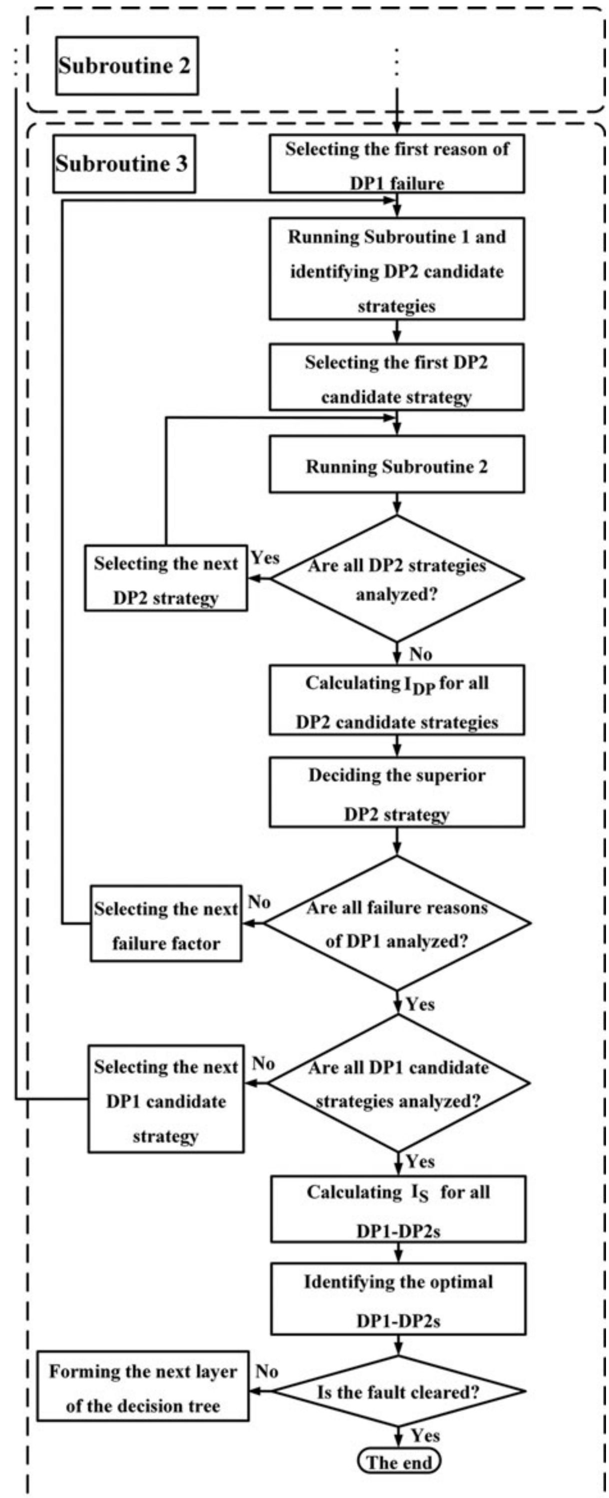
FIGURE 5. The process of forming the proposed DT.



b

FIGURE 5. (Continued).

strategies are determined. Finally, in subroutine 3 the optimal sequence of DP1–DP2s is identified.

4. SIMULATION AND RESULTS

In order to test efficiency of the proposed method of this paper, it is implemented on sample microgrid of Figure 6 which is also used in [24]. This system is fed from medium voltage network at buses 1 and 5. The loads shown in Figure 6 are the rated loads. Similar to [22], I_{R_B} and I_{U_B} of all CBs are assumed to be 1.25 and 10 kA, respectively.

In this paper, the fiber-optic links are used in order to settle the communication between the central server and each CB. These links are used due to their lower latency and higher band width comparing to other communication links [20]. Standard latency of these links has been estimated 0.005 ms/km [21]. This value is assumed for latency of communication links in the presented paper.

This should be mentioned that, while calculating the latency of paths that use communication links among CBs, the latency of communication link that sends this command to communication link among CBs should be considered. For instance, latency of the path which uses L_{1-2} to send command to B_2 equals to the time latency of communication links of L_1 and L_{1-2}.

According to the latency of communication links and the probability density function presented in [20], the probability of correct operation of communication links is assumed to be similar with values of Table 1.

In order to evaluate the results of implementing the proposed approach, the reaction of this method in F1 point of Figure 6 in two different topologies is analyzed by DIgSILENT Power Factory software. In the first topology, similar to the assumption that is made in [24], two 5 (MW) DGs are connected to busses 4 and 8. In the second topology, in addition to DGs of the first topology, another 5 (MW) DG is connected to bus 12. In both situations, since the lowest outage in DP1 strategy of each layer is desired, the coefficients α and β in Eq. (7) are assumed to be 2 and 1, respectively. In addition, to balance the sentences of Eq. (7), weighting coefficients of δ and η are assumed to be 3 and 1, respectively.

Point	Latency (ms)	Probability	Point	Latency (ms)	Probability
1	0.005	0.05	5	0.025	0.2
2	0.01	0.1	6	0.03	0.1
3	0.015	0.2	7	0.035	0.05
4	0.02	0.3			

TABLE 1. Probability density function of the latency of the communication links.

4.1. Assessing the Proposed Method when DG3 is Disconnected

In this topology, fault current which flows through each CB of protective layer is presented in Table 2. In addition, Table 3 shows the status of various strategies for three levels of the protective layer. As it is clear, strategy 3 created the lowest IN_{LA} among the second-level strategies of the protective layer. Therefore, this strategy alongside the first-level strategy is a candidate for inclusion in the DP1 of DT. Results of Table 3 show that none of the third-level strategies of the protective layer could establish the IN_{LA} lower than the second layer. Thus, only strategies 1 and 3 are candidates for inclusion in DP1.

For each of the failure causes of candidate DP1 strategies, a protective layer is formed and candidate DP2 strategies are determined. Table 4 shows the status of DP2 strategies when the candidate strategy 1 cannot clear the fault due to failure in B_{14}. As Table 4 shows, due to the use of B_{14}, strategies 1, 3, and 9 cannot be candidate for inclusion in DP2 for this case. Moreover, according to calculated indices, strategies 2 and 6 are selected as DP2 candidate strategies for this case of failure of DP1 strategy.

Table 5 shows all DP2 candidate strategies for each of the failure causes of DP1 candidate strategies. As shown in the table, among DP2 candidate strategies, the best strategy is determined using Eq. (7). In Table 5, the IN_{SA} is calculated for all DP1-DP2s. As can be seen, DP1 = 1 and all of its DP2 strategies establish the lowest index. Therefore, as shown in Figure 7, these strategies are included in the first layer of the DT to clear the fault. Sequence of applying strategies in the DT of Figure 7 clearly highlights the difference between the proposed method and traditional protection coordination schemes. For example, in traditional protection methods which are realized using directional relays (such as the methods presented in [5], [7], [25]), when strategy 1 cannot clear the fault because of failure in B_{14}, strategy 5 will replace it. However, in the proposed method, strategy 6 was selected due to making decisions with regard to the healthiness of CBs and communication links. This should be mentioned that in order to simplify Figure 7, terminal nodes are not considered.

It is assumed that strategy 1 cannot clear the fault because of failure in B_{14} and strategy 6 because of failure in L_{14-13}. Thus, as shown in Figure 7, another arrangement of DP1-DP2s must be established from where previous strategies have failed. As can be seen in Figure 7, strategies 4 and 6 are

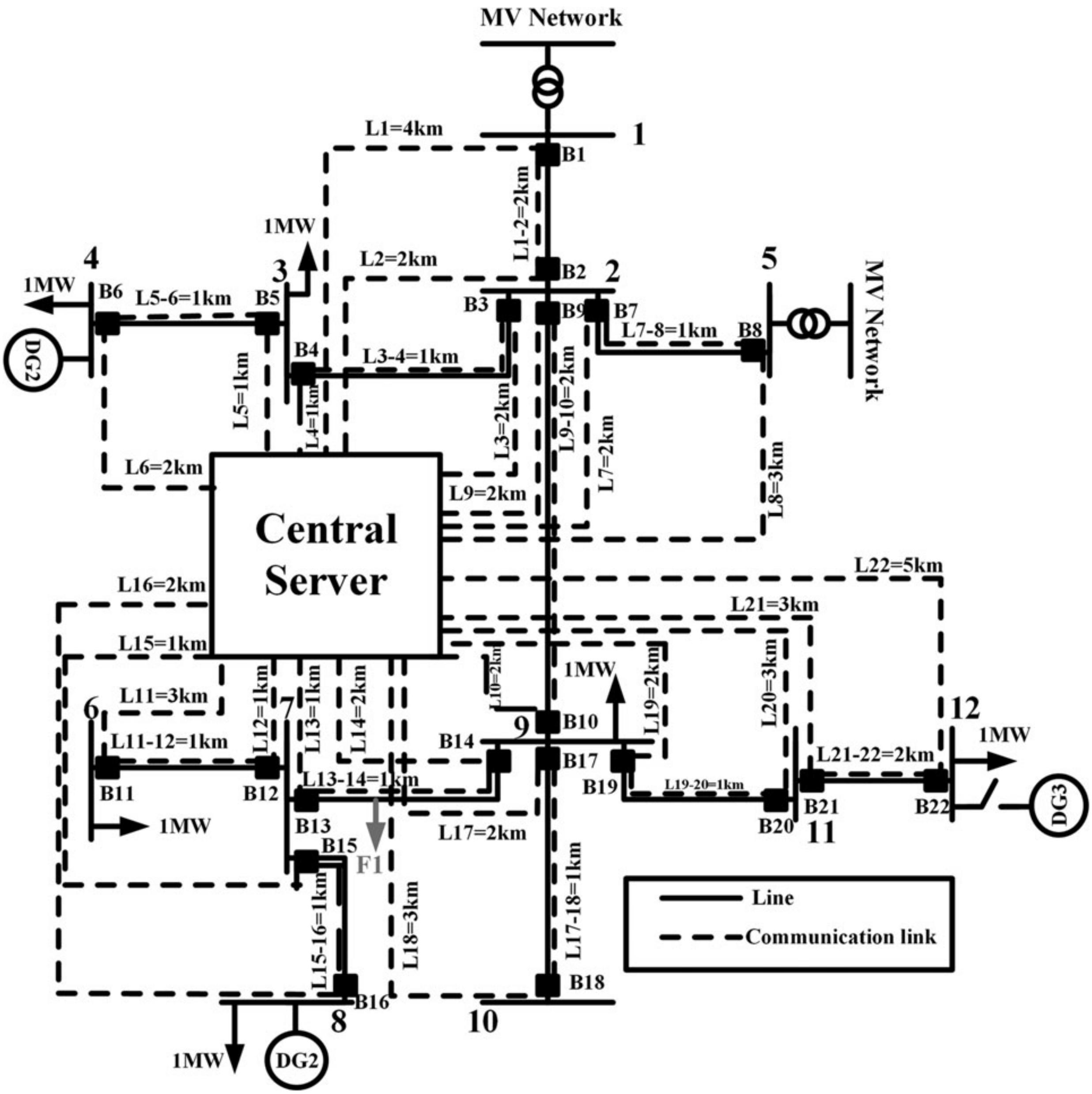


FIGURE 6. Sample microgrid with central server for implementing the proposed method.

selected, respectively, as the DP1–DP2s of the second layer of the DT.

4.2. Assessing the Proposed Method when DG3 is Connected

As DG3 connects to bus 12, the amount and direction of the fault current in the microgrid will change. Therefore, the protection system must make decisions according to the new conditions. DT in Figure 8 shows the optimal arrangement of strategies for this case. As it is clear, according to the new microgrid topology, the protection system has established a different arrangement of strategies compare to case 1. Moreover, due to the involvement of DG3 in supplying the fault current, CBs and communication links involved in strategies are also different from case 1. Table 6 shows CBs and communication links involved in the first, second, and third level strategies of the protective layer

CB number	Short circuit current (kA)	CB number	Short circuit current (kA)	CB number	Short circuit current (kA)
1	1.67	9	5.67	17	0
2	1.67	10	5.67	18	0
3	0.75	11	0	19	0
4	0.75	12	0	20	0
5	0.77	13	3.03	21	0
6	0.77	14	5.65	22	0
7	3.27	15	3.03		
8	3.27	16	3.03		

TABLE 2. Short circuit current of all CBs in case 1.

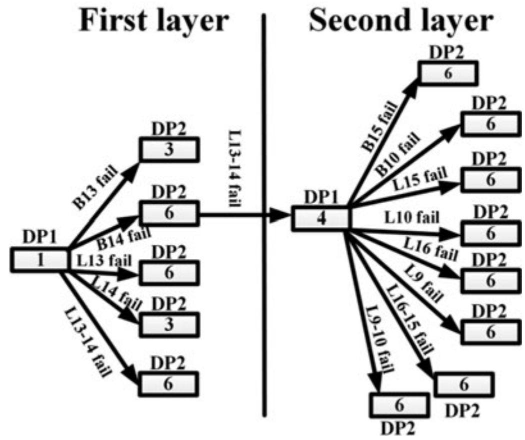


FIGURE 7. DT in case 1.

that are involved in the formation of the DT shown in Figure 8.

In order to test the presented method, it is compared with [5]. In [5] traditional protection coordination which is achieved with local decisions is used for clearing fault.

Figure 9 represent the behavior of protection system for a fault in F1 point in [5]. It is assumed that DG3 is separate from the network. Comparing the protection system behavior of Figures 7 and 9 shows that both methods select traditional strategy which is achieved by B_{13}, B_{14} CBs for the first level of clearing fault. According to Figure 7, if there was a problem in B_{14} and it failed to clear the fault, the presented method of this paper selects B_{13}, B_2, B_3, B_7 CBs as the backup strategy. As it is clear from Table 4, the probability of correct operation of this strategy is 0.43 and its load outage is 2(MW), while according to Figure 9, the presented method of [5] selects B_{13}, B_9 CBs. According to Table 2, it is clear that short circuit current of B_9 is 5.67(kA). In traditional protection systems (such as [5], and [26]), coordination time interval is assumed to be 0.4(s). Therefore, at least 0.4(s) is required for B_{13}, B_9 strategy to start clearing the fault as a substitute for B_{13}, B_{14} strategy. Using Eq. (5), it is clear that B_9 would certainly fail to clear the fault in this time. Therefore, another strategy (such as B_{13},

Strategy number	Involved CBs	Involved communication links	L^S_{Loss} (MW)	t^S_{Apply}(ms)	$P^S_{Strategy}\,(I^S_F, t^S_{L\mathrm{Max}})$	IN_{LA}
		The first level				
1	B_{13}, B_{14}	$L_{13}, L_{14}, L_{13-14}, L_{14-13}$	0	0.015	0.0827	0
		The second level				
2	B_{13}, B_{10}	$L_{13}, L_{10}, L_{14}, L_9, L_{14-13}, L_{9-10}$	2	0.02	0.372	5.38
3	B_{15}, B_{14}	$L_{15}, L_{14}, L_{13}, L_{16}, L_{13-14}, L_{16-15}$	1	0.015	0.392	2.55
4	B_{15}, B_{10}	$L_{15}, L_{10}, L_{16}, L_9, L_{16-15}, L_{9-10}$	3	0.02	0.372	8.06
		The third level				
5	B_{13}, B_9	$L_{13}, L_9, L_{14}, L_{10}, L_{14-13}, L_{10-9}$	2	0.02	0.403	4.96
6	B_{13}, B_2, B_3, B_7	$L_{13}, L_2, L_3, L_7, L_{14}, L_1, L_4, L_8, L_{14-13}, L_{1-2}, L_{4-3}, L_{8-7}$	2	0.02	0.458	4.36
7	B_{15}, B_2, B_3, B_7	$L_{15}, L_2, L_3, L_7, L_{16}, L_1, L_4, L_8, L_{16-15}, L_{1-2}, L_{4-3}, L_{8-7}$	3	0.02	0.424	7.07
8	B_{15}, B_9	$L_{15}, L_9, L_{16}, L_{10}, L_{16-15}, L_{10-9}$	3	0.02	0.372	8.06
9	B_{16}, B_{14}	$L_{16}, L_{14}, L_{15}, L_{13}, L_{15-16}, L_{13-14}$	1	0.01	0.037	27.02
10	B_{16}, B_{10}	$L_{16}, L_{10}, L_{15}, L_9, L_{15-16}, L_{9-10}$	3	0.02	0.335	8.95
11	B_{16}, B_9	$L_{16}, L_9, L_{15}, L_{10}, L_{15-16}, L_{10-9}$	3	0.02	0.335	8.95
12	B_{16}, B_2, B_3, B_7	$L_{16}, L_2, L_3, L_7, L_{15}, L_1, L_4, L_8, L_{15-16}, L_{1-2}, L_{4-3}, L_{8-7}$	3	0.02	0.408	7.35

TABLE 3. Status of strategies of three levels of protective layer for case 1.

Strategy number	Involved CBs	Involved communication links	L^S_{Loss} (MW)	t^S_{Apply} (ms)	$P^S_{Strategy}$ (I^S_F, $t^S_{L_{Max}}$)	IN_{LA}
		The second level				
2	B_{13}, B_{10}	L_{13}, L_{10}, L_{14}, L_9, L_{14-13}, L_{9-10}	2	0.035	0.335	5.97
4	B_{15}, B_{10}	L_{15}, L_{10}, L_{16}, L_9, L_{16-15}, L_{9-10}	3	0.035	0.335	8.95
		The third level				
5	B_{13}, B_9	L_{13}, L_9, L_{14}, L_{10}, L_{14-13}, L_{10-9}	2	0.035	0.389	5.14
6	B_{13}, B_2, B_3, B_7	L_{13}, L_2, L_3, L_7, L_{14}, L_1, L_4, L_8, L_{14-13}, L_{1-2}, L_{4-3}, L_{8-7}	2	0.035	0.434	4.6
7	B_{15}, B_2, B_3, B_7	L_{15}, L_2, L_3, L_7, L_{16}, L_1, L_4, L_8, L_{16-15}, L_{1-2}, L_{4-3}, L_{8-7}	3	0.035	0.402	7.46
8	B_{15}, B_9	L_{15}, L_9, L_{16}, L_{10}, L_{16-15}, L_{10-9}	3	0.035	0.335	8.95
10	B_{16}, B_{10}	L_{16}, L_{10}, L_{15}, L_9, L_{15-16}, L_{9-10}	3	0.035	0.302	9.93
11	B_{16}, B_9	L_{16}, L_9, L_{15}, L_{10}, L_{15-16}, L_{10-9}	3	0.035	0.302	9.93
12	B_{16}, B_2, B_3, B_7	L_{16}, L_2, L_3, L_7, L_{15}, L_1, L_4, L_8, L_{15-16}, L_{1-2}, L_{4-3}, L_{8-7}	3	0.035	0.387	10.33

TABLE 4. DP2 strategies when DP1 = 1 fails because of the B_{14} failure.

Candidate strategy for DP1	Defective component	Candidate strategies for DP2	Superior candidate strategy for DP2	IN_{SA}
1	B_{13}	3	3	4.08
	B_{14}	2, 6	6	
	L_{13}	1, 2, 6	6	
	L_{14}	1, 3	3	
	L_{13-14}	1, 4, 6	6	
3	B_{14}	2, 6	6	4.77
	B_{15}	1, 3, 6	1	
	L_{14}	1, 3	1	
	L_{15}	1, 2, 6	1	
	L_{13}	1, 2, 6	1	
	L_{16}	1, 2, 6	1	
	L_{13-14}	1, 4, 6	1	
	L_{16-15}	1, 2, 6	1	

TABLE 5. Determining the best DP1–DP2s for case 1.

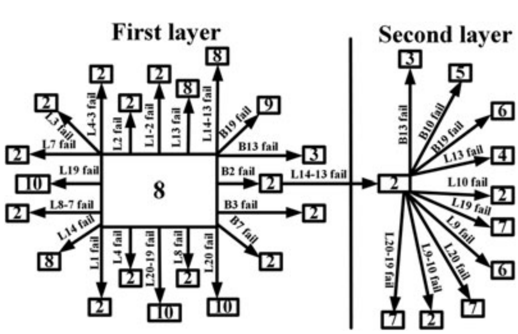


FIGURE 8. DT in case 2.

B_1, B_4, B_8) will start clearing the fault after 0.4(s). According to the fault currents of CBs and using Eq. (5), B_8 cannot also clear the fault and it will result in total black out in the network.

Therefore, it is clear that using the global decision making which is achieved by central server can select the best protection coordination strategy according to the network topology and probability of correct operation of protection system. In addition, proposed method of this paper solves problems of similar studies. Accordingly, unlike the methods presented in [3], [6], the proposed method does not need to store large volumes of settings. Moreover, compared to the methods proposed in [5], [8] which use the fault current limiter (FCL) to secure protection coordination, the presented method can respond to all network topologies while presented methods of [5], [8] after installing FCLs can respond to a limited topologies. Compared with protection coordination methods which use extensive communication links (such as [10], [12]), the proposed method does not use offline decisions, and also can make decisions based on the microgrid topology and the probability of proper operation of CBs and communication links. This increases the method reliability.

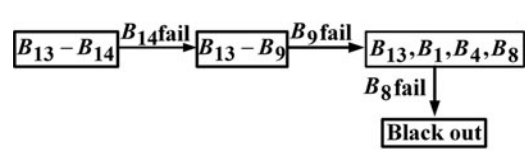


FIGURE 9. The reaction of the proposed protection system in [5] during F1 fault and when DG3 is disconnected.

Strategy number	Involved CBs	Involved communication links
		The first level
1	B_{13}, B_{14}	$L_{13}, L_{14}, L_{13-14}, L_{14-13}$
		The second level
2	B_{13}, B_{10}, B_{19}	$L_{13}, L_{10}, L_{19}, L_{14}, L_{9}, L_{20}, L_{14-13}, L_{9-10}, L_{20-19}$
3	B_{15}, B_{14}	$L_{15}, L_{14}, L_{13}, L_{16}, L_{13-14}, L_{16-15}$
4	B_{15}, B_{10}, B_{19}	$L_{15}, L_{10}, L_{19}, L_{16}, L_{9}, L_{20}, L_{16-15}, L_{9-10}, L_{20-19}$
	The third level	
5	B_{13}, B_{9}, B_{19}	$L_{13}, L_{9}, L_{19}, L_{14}, L_{10}, L_{20}, L_{14-13}, L_{10-9}, L_{20-19}$
6	B_{13}, B_{9}, B_{20}	$L_{13}, L_{9}, L_{20}, L_{14}, L_{10}, L_{19}, L_{14-13}, L_{10-9}, L_{19-20}$
7	B_{13}, B_{9}, B_{21}	$L_{13}, L_{9}, L_{21}, L_{14}, L_{10}, L_{22}, L_{14-13}, L_{10-9}, L_{22-21}$
8	$B_{13}, B_{2}, B_{3}, B_{7}, B_{19}$	$L_{13}, L_{2}, L_{3}, L_{7}, L_{19}, L_{14}, L_{1}, L_{4}, L_{8}, L_{20}, L_{14-13}, L_{1-2}, L_{4-3}, L_{8-7}, L_{20-19}$
9	$B_{13}, B_{2}, B_{3}, B_{7}, B_{20}$	$L_{13}, L_{2}, L_{3}, L_{7}, L_{20}, L_{14}, L_{1}, L_{4}, L_{8}, L_{19}, L_{14-13}, L_{1-2}, L_{4-3}, L_{8-7}, L_{19-20}$
10	$B_{13}, B_{2}, B_{3}, B_{7}, B_{21}$	$L_{13}, L_{2}, L_{3}, L_{7}, L_{21}, L_{14}, L_{1}, L_{4}, L_{8}, L_{22}, L_{14-13}, L_{1-2}, L_{4-3}, L_{8-7}, L_{22-21}$

TABLE 6. CBs and communication links involved in the DT for case 2.

5. CONCLUSION

To create accountability power in the protection system against the uncertainties affecting the protection coordination of microgrids, this paper proposed a new method of protection coordination. By creating a decision tree, the new method determines the optimal arrangement of applying strategies according to the microgrid topology and the probability of proper operation of CBs and communication links in such a way that the strategy which has minimum load outage and maximum proper operation is a candidate for clearing the fault. The probability of the proper operation of CBs and communication links is not considered constant but variable, respectively, proportional to the fault current flowing through the CBs and the amount of latency of communication links. The results of implementing the proposed method on different topologies of a sample microgrid prove that this method is successful in establishing protection coordination given the uncertainty in the microgrid topology and the proper operation of CBs and communication links. Selecting optimal strategy for clearing faults not necessarily leads to the closest protection systems to clear faults and this issue represents the difference of the proposed approach to traditional protective plans. Moreover, due to the fact that there is no need to predict the microgrid topologies and store their respective protection coordination settings in the proposed method, the protection system can create the optimal protection coordination in each microgrid topology.

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