A Decentralized Adaptive Scheme for Protection Coordination of Microgrids Based on Team Working of Agents

Seyed Amir Hosseini
Department of Electrical Engineering Golpayegan University of Technology
Isfahan, Iran
hosseini.amir@gut.ac.ir

Seyed Hossein Hesamedin Sadeghi
Department of Electrical Engineering
Amirkabir University of Technology
Tehran, Iran
Dep. of Electrical Eng. and Comp.Science
University of Wisconsin-Milwaukee
Milwaukee, USA
sadeghi@aut.ac.ir

Adel Nasiri
Dep. of Electrical Eng. and Computer Science
University of Wisconsin-Milwaukee
Milwaukee, USA
nasiir@uwm.edu

***Abstract*—A decentralized adaptive scheme is proposed for protection coordination of microgrids. In the proposed scheme, a set of agents around the fault location negotiate with each other to reach the best protection coordination strategy upon the occurrence of a fault. Adopting a protective layer, agents are arranged in a number of groups where the members in each group can interact with each other. Considering the operational uncertainties of the respective circuit breakers and communication links, the best fault clearance strategy is determined by analyzing the probability of correct operation of all proposed strategies and considering the least number of probable outages. This is done by calculating the fault currents flowing through the respective circuit breakers and the latency of the communication links. The efficiency of the proposed scheme is demonstrated by comparing the simulation results of a sample network with those obtained using the conventional central adaptive protection approach.**

Keywords—Microgrid; Agent; Protection Coordination; Team Working; Uncertainty

I. INTRODUCTION

Microgrid is a dynamic structure that suffers from topological uncertainties due to connection/disconnection of distribution generation (DG) resources and operation in normal and islanded modes [1-3]. Given the multiplicity of microgrid operational topologies and the fact that calculations of protection coordination are time-consuming, the protection coordination in these networks becomes a complicated task [4, 5]. To deal with the problem, offline saving of relays settings for possible operational topologies has been proposed [6-8]. While this approach can be used for some microgrids, it is not a practical solution to tackle the problem at its roots for not addressing the limited relay on-board storage and the impossibility of predicting all operational topologies [9, 10].

Apart from the structural uncertainties of the microgrid, the operational uncertainties of protection systems has also a complex nature, making the task of protection coordination even more difficult with possible undesired outages and reduced network reliability [11, 12]. However, with the advent of high-speed and reliable communication networks, various adaptive schemes have been devised for protection of microgrids in the presence of uncertainties [13]. In these schemes, data is shared between various protection system agents, and the best fault clearance decision is made adaptively from a set of stored offline decisions [14-16].

For a proper operation of an adaptive protection coordination scheme, the inevitable operational uncertainties in communication links should also be considered [17, 18]. To deal with the uncertainties in microgrid topology, protection system and communication links, several adaptive schemes have been proposed [19]. The core design of most of these schemes is based on the existence of a central server that is responsible for selecting the best strategy for clearing a fault

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[20, 21]. The main shortcoming in these schemes is neglecting the uncertainty in the correct operation of the central server.

In this study, a decentralized adaptive scheme is proposed to provide protection coordination in a microgrid by taking into account the uncertainties in the microgrid topology, protection system, and communication links. The probability of correct operations of protection system and communication links are assumed to be functions of the fault current passing through circuit breakers (CBs) and the latency of the communication links, respectively. In the proposed scheme, a set of agents around the fault location negotiate with each other to reach the best protection coordination strategy. Adopting a protective layer, agents are arranged in a number of groups where the members in each group can interact with each other. In this scheme, the closest protection systems are not necessarily activated in the event of a fault. Instead, the best strategy will be selected by ensuring the highest probability for correct operation of the protection system and communication links with a minimum number of outages.

The manuscript is structured as follows. In Section II, the conceptual design of the proposed scheme is described. Also, the steps required to determine the best strategy for clearing a fault are detailed. In Section III, the efficiency of the proposed scheme is demonstrated by comparing the simulation results of a sample network with those obtained using the conventional central adaptive protection approach.

II. Proposed Scheme

A. Conceptual design

The conceptual design of the proposed scheme is presented in Fig. 1. Following the occurrence of a fault, a group of agents, acting as the protective layer, cooperate and share their information. The agents group assesses all possible scenarios in the protective layer that may successfully clear the fault. The strategy that offers the minimum outages with the highest probability of correct operation is selected as the "superior" strategy for clearing the fault. If the selected strategy successfully clears the fault, the system returns to its initial state prior to the occurrence of the fault, being ready for the next fault. Otherwise, another superior strategy is selected to clear the fault.

It is noted that not all grid agents are required to be present in the group assigned for clearing a fault. For example, agents far away from the fault location are less likely to contribute to the selection of a superior strategy. This is due to the fact that operation of such agents affects a larger section of the microgrid, causing undesired excessive outages.

To further reduce the number of agents in the group (to limit the number of potential superior strategies), we adopt a protective layer such as that proposed in [20]. In this layer, the agents at the two sides of the fault location as well as its neighboring agents are involved in forming the group. For example, in the network shown in Fig. 2, the agents $A_2, A_3, A_7, A_8, A_9, A_{11}$ are included in the group in the event of fault F1.

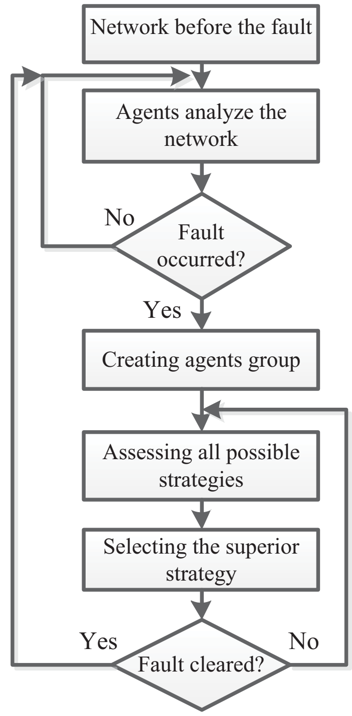

Fig. 1. The conceptual design for the proposed method

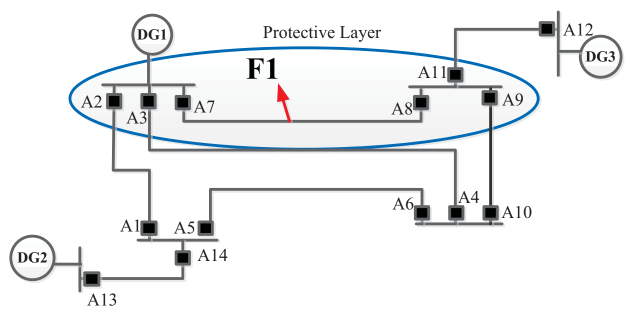

Fig. 2. Protective layer for clearing fault F1

B. Probability of correct operation of the protection system

The correction operation of a multi-agent protection system relies on the performance of individual agents. Each agent consists of a computation unit, protection devices and communication links for connecting it to other agents. Assuming that computation units are flawless, we focus only on the probability of correct operation of protection devices and communication links.

The probability of correct operation of protection devices is evaluated by computing the probability of correct operation of its CBs. This is due to the fact that CBs are the most affected protection devices [22]. Given that the performance of a CB is directly related to the fault current intensity and duration, the probability of correct operation of the B-th CB, $P_s^B(t_s, I_F)$, can be obtained as follows [23].

$$P_s^B(t_s, I_F) = \begin{cases} 1 & ; if\ I_F^B \le I_R^B \\ 1-(I_F^B - I_R^B).t_s & ; if\ I_U^B > I_F^B > I_R^B \\ 0 & ; if\ I_F^B \ge I_U^B \end{cases} \quad (1)$$

where $I_F^B(t)$ and I_R^B are, respectively, the actual and nominal fault currents passing through the *B*-th circuit breaker, and t_s denotes the sum of the time required for the agents to share their information and the operating time of the respective superior strategy. Note that a CB will definitely perform correctly if the fault current through it is lower than its nominal value (I_R^B); it will definitely fail if the respective fault current exceeds a known failure threshold (I_U^B).

The probability of correct operation of communication links is proportional to their time delays, being dependent on the link type and length [24, 25]. We assume that fiber-optic cables are used for their lower time delay and higher bandwidth compared to other communication links. Considering that the communication links in the proposed scheme are solely used to share the information between the agents, the probability of correct operation of communication links associated with the *S*-th candidate strategy, can be expressed as follows [21].

$$P_s^{Link}(t_s) = \prod_{L=1}^{L_s}(P_L) \quad (2)$$

where P_L is the number of the point related to the probability of correct operation of *L*-th link in the probability distribution table for the communication links, and L_s is the total number of communication links involved in the selection of the *S*-th strategy.

Having determined the values of $P_s^B(t_s, I_F)$ and $P_s^{Link}(t_s)$, the probability of correct operation of the protection system associated with the *S*-th candidate strategy, can be obtained by multiplying Eqs. (1) and (2), *i.e.*,

$$P_s(t_s, I_f) = P_s^{Link}(t_s) \times P_s^B(t_s, I_f) = \prod_{L=1}^{L_s}(P_L(i)) \times \prod_{C=1}^{CB_s} P_B^C(t_s, I_f) \quad (3)$$

where CB_s is the total number of CBs involved in the *S*-th candidate strategy.

C. Selection of a superior strategy

Among all candidate strategies in the protective layer, a superior strategy is the one that offers the minimum outages ($Min(Load_{Loss})$) as well as the highest probability of correct operation ($Max(P_s)$) by taking into account the operational uncertainties of the protection system and the communication links. To this end, the agents in the protective layer weigh all candidate strategies by computing their respective "superiority" index, SI, defined as follows,

$$SI = Min(Load_{Loss}).Max(P_s) \quad (4)$$

The candidate strategy with the lowest value of SI is selected as the superior strategy.

III. Simulation Results

In order to assess the efficiency of the proposed scheme, it is implemented on the sample microgrid shown in Fig. 3. For the sake of comparison, the grid is the same as that used in [21] where a centralized adaptive scheme is adopted for dealing with uncertainties. The grid data are given in [21], and for lack of space, are not repeated here.

A. Single fault

In the first case study, we examine the performance of the proposed scheme in dealing with a single fault occurred at F1, Fig. 3. Here, agents A_2, A_3, A_4, A_5 perform as the protective layer. The short-circuit currents passing through these agents are given in Table I.

TABLE I. Short circuit current passing through agents in the protective layer during fault F1

Agent number	Short circuit current (kA)	Agent number	Short circuit current (kA)	Agent number	Short circuit current(kA)
2	3.96	4	4.42	6	4.42
3	3.96	5	4.42		

Assuming that DG1 and DG2 are set to "On", fault F1 is supplied from both sides. It follows that the agents on both sides of the fault will react to clear it. The results of evaluating various strategies that are capable of clearing the fault is given in Table II. From the results shown in Table II, it is deduced that strategy 1 is the best choice for clearing the fault. Comparison of the results with those of [21] suggests that the same strategy is considered "superior" in both studies. However, the probability of correct operation for the proposed scheme is considerably higher than that given in [21]. This is sought to be due to the fact that in [21] all the necessary information should be transferred to a central server, whereas in the proposed scheme the decisions are made locally. Note that the augmented number of communication links in the former scheme increases operation uncertainty which, in turn, reduces the probability of correct operation of the superior strategy. Moreover, the security of the proposed method is considerably higher since not the entire information is needed to be transferred to the central server.

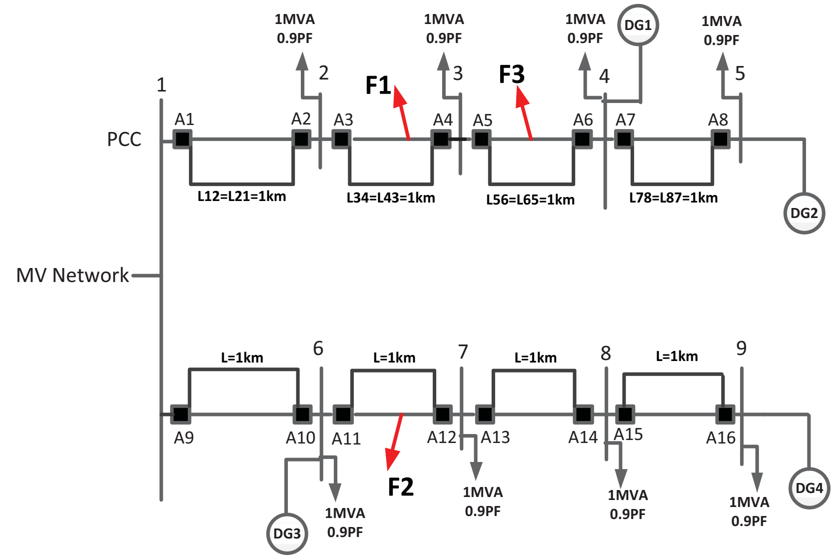

Fig. 3. Sample microgrid for implementing the proposed protection coordination scheme

TABLE II. VARIOUS STRATEGIES CONSIDERED DURING FAULT F1 IN FIG. 3.

Strategy number	Involved agents	$P_s(t_s, I_f)$	$Load^S_{Loss}(MVA)$
1	A_3, A_4	0.147	0
2	A_2, A_4	0.147	1
3	A_2, A_5	0.147	2
4	A_3, A_5	0.148	1

B. *Simultaneous faults*

In the next case study, we consider simultaneous faults in the microgrid. Let us assume faults F1 and F2 occur concurrently, as shown in Fig. 3. Here, agents A_2, A_3, A_4, A_5 assess all possible strategies to clear fault F1 while agents $A_{10}, A_{11}, A_{12}, A_{13}$ are responsible for clearing fault F2. The results of evaluating these strategies for both faults are presented in Table III. According to this table, strategies 1 and 5 are found to be the best choices for clearing faults F1 and F2, respectively. The agents states in these strategies are demonstrated in Figs. 4 and Fig. 5, respectively. Notice that the simultaneous faults are cleared successfully by the operation of the engaged CBs in each selected superior strategy.

Assuming that both faults F1 and F3 occur simultaneously, the state of the protective layer for these two faults is demonstrated in Fig. 6. As shown in this figure, the appropriate strategies to clear the faults F1 and F3 should be determined using agents A_2, A_3, A_4, A_5 and agents A_4, A_5, A_6, A_7, respectively.

The results shown in Table IV display the agents involved in the process of selecting the candidate strategies in each created protective layer. Referring to table IV, it is noted that agents A_4, A_5 are shared between the two protective layers. The problem here is to determine to which group agents A_4, A_5 belong. Clearing simultaneous faults in the proposed scheme faces a serious challenge without initially providing an answer to this question. In other words, the proposed scheme can only deal with simultaneous faults when no common agents are shared between the protective layers.

TABLE III. VARIOUS STRATEGIES CONSIDERED DURING SIMULTANEOUS FAULTS F1 AND F2 IN FIG. 3.

Fault F1			
Strategy number	***Involved agents***	$P_s(t_s, I_f)$	$Load^S_{Loss}(MVA)$
1	A_3, A_4	0.150	0
2	A_2, A_4	0.150	1
3	A_2, A_5	0.150	2
4	A_3, A_5	0.151	1
Fault F2			
Strategy number	***Involved agents***	$P_s(t_s, I_f)$	$Load^S_{Loss}(MVA)$
5	A_{11}, A_{12}	0.146	0
6	A_{10}, A_{12}	0.146	1
7	A_{10}, A_{13}	0.146	2
8	A_{11}, A_{13}	0.148	1

TABLE IV. INVOLVED AGENTS IN DIFFERENT STARATEGIES FOR CLEARING SIMULTANEOUS FAULTS F1 AND F3 IN FIG. 3.

Fault F1		**Fault F2**	
Strategy number	***Involved agents***	***Strategy number***	***Involved agents***
1	A_3, A_4	1	A_4, A_6
2	A_2, A_4	2	A_4, A_7
3	A_2, A_5	3	A_5, A_6
4	A_3, A_5	4	A_5, A_7

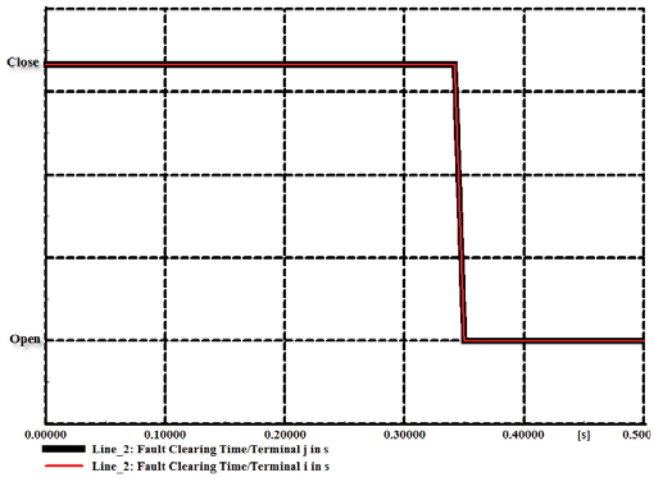

Fig. 4. Status of agents A_3 and A_4 during simultaneous faults F1 and F2

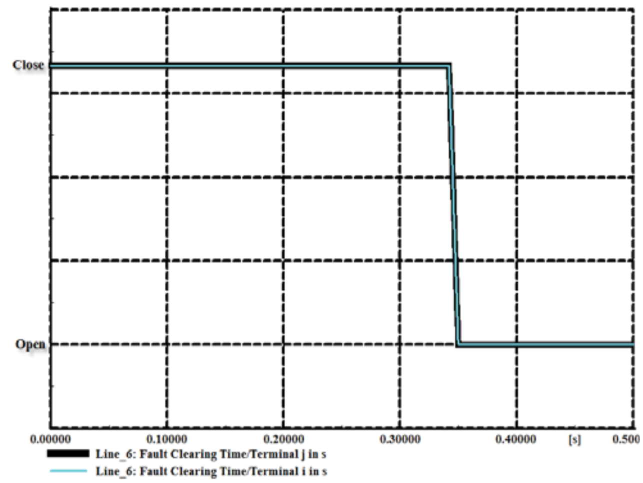

Fig. 5. Status of agents A_{11} and A_{12} during simultaneous faults F1 and F2

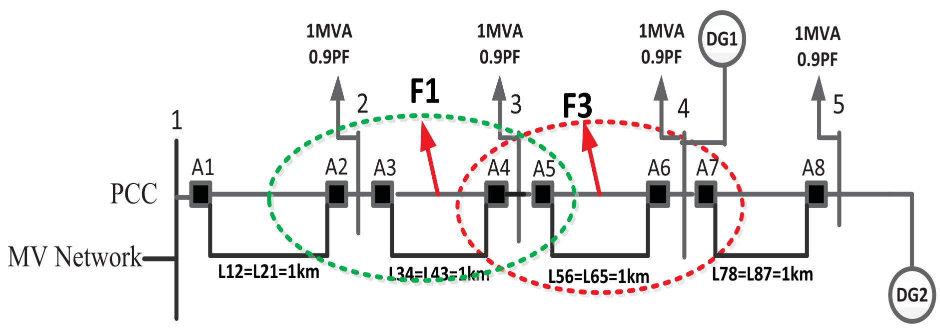

Fig. 6. Protective layers for simultaneous faults F1 and F3

IV. Conclusions

In this study, a decentralized scheme has been proposed to coordinate the protection of a microgrid when considering the structural uncertainties of the microgrid as well as the operational uncertainties of the respective circuit breakers and communication links. The main feature of the proposed scheme is related to appropriate negotiations protocols among protection agents that enable local decision making. It has been shown that the proposed scheme is more efficient than those taking advantage of central adaptive protection approaches. Besides, the proposed scheme, unlike its counterparts, is capable of dealing with simultaneous faults given that no common agents are shared between the two groups.

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