

Fast Protection Scheme for Active Distribution Networks: Breaking Chains by Utilizing Auxiliary Relays

Amin Yazdaninejadi, Daryoush Nazarpour, and Vahid Talavat

Abstract—Due to the swift expansion and the deployment of distributed generation, protection systems of active distribution networks are more expected to be fast. In loop-based active distribution networks, directional overcurrent relays (DOCRs) are caught in different chains. These chains stand as the severe obstacle to follow fast-response protection, which remains a significant challenge. In this paper, to overcome this challenge, a fast protection scheme is proposed to break the chains in the corresponding loops by deploying auxiliary DOCRs. The most effective constraint associated with each chain is relaxed during the coordination process. Then, the auxiliary relays are employed to play the backup roles instead of conventional backup relays in the relaxed constraints. To avoid the misoperation of relays in the proposed scheme, low bandwidth communication links are suitably employed. Furthermore, the auxiliary relays are optimally placed and adjusted. The proposed approach demonstrates a mixed-integer nonlinear programming model which is tackled by particle swarm optimization (PSO) algorithm. Detailed simulation studies are carried out to verify the performance of the proposed approach.

Index Terms—Fast protection scheme, directional overcurrent relays, active distribution network, backup relay, auxiliary relay.

I. INTRODUCTION

REGARDING the bidirectional power flow in distribution networks with loop-based structure, directional overcurrent relays (DOCRs) are commonly deployed in these networks [1]. However, their coordination poses a complicated programming challenge [2], which results in higher tripping time for the relays. Fast-response protection system plays a vital role in minimizing the level of power equipment damage, preventing disconnections of unintentional feeder or distributed generation (DG), and decreasing the probability of instability and even enhancing the power quality metrics [3]. Therefore, a fast protection scheme is of vital importance in these networks.

To date, several researchers have endeavored to tackle the technical hurdles of overcurrent relays. In this way, trial and error methods have been employed in [4], [5]. Due to the high computation burden, these methods would not be suitable for practical implementations. Linear programming methods are also examined in [6], [7]. The need for initial guess is the key limitation of these methods which increases the probability of trapping in local minima. [2]. In [8]-[10], nature-inspired and artificial intelligence algorithms are applied to respond to the coordinated challenge. Furthermore, in [11], a comparative study is explored to highlight the best optimization algorithm for DOCR coordination. To escape local minima and enhance the technical metrics of protection coordination, different penalty methods are adopted in [12]-[14] besides the main objective. Although these methods are efficient in finding proper solutions, the obtained reductions in tripping time of relays are not considerable.

Numerical relays render plenty of features that pave the way for launching different coordination strategies. These relays allow the users to graphically outfit arbitrary time-current characteristics or in a table form [15], [16]. In [17], based on the deployment of these relays, different standard characteristics are employed in coordination process extended in [18]. By deploying these relays, the flexibility in relay is augmented, which helps to yield a fast-response protection system. However, these schemes require to replace all conventional relays with digital ones. In [19], the performance of the protection system is improved based on wide-area monitoring. Meanwhile, the employment of communication links increases the failure risk of backup relay.

In this paper, we aim to reduce the tripping time of DOCRs in loop-based active distribution networks. At the outset, this paper unveils that DOCRs are caught in different chains of such networks. These chains stand as a severe obstacle to follow fast-response protection. Therefore, a fast protection scheme is proposed that exploits auxiliary relays to break the chains in the corresponding loops. Auxiliary relays help to relax the severest constraints of chains in the coordination process and hence yield simpler optimization space. Thereby, the simplification results in a faster protection system. Although the mentioned relaxation takes some of the conventional backup relays away from the coordination process, the auxiliary relays stand as new backup relays in the proposed scheme. Moreover, to avoid the misopera-

Manuscript received: August 13, 2018; accepted: October 16, 2019. Date of CrossCheck: October 16, 2019. Date of online publication: April 29, 2020.

This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>).

A. Yazdaninejadi (corresponding author) is with the Department of Electrical Engineering, Shahid Rajaee Teacher Training University, Tehran, Iran (e-mail: a.yazdaninejadi@sru.ac.ir).

D. Nazarpour and V. Talavat are with Urmia University, Urmia, Iran (e-mail: d.nazarpour@urmia.ac.ir; v.talavat@urmia.ac.ir).

DOI: 10.35833/MPCE.2018.000534



tion of relays in the proposed scheme, low-bandwidth communication links are employed properly. Instead of conventional backup relays in the relaxed constraints, the auxiliary relays are coordinated with corresponding primary relays in the coordination process. Therefore, low-bandwidth communication links are considered to block conventional backups. In the proposed scheme, the auxiliary relays are optimally placed and adjusted. The main contributions of the proposed scheme could be listed as follows:

1) An illustration-based analysis is carried out to show that DOCRs are caught in different chains of loop-based networks, which stands as an obstacle to follow fast-response protection.

2) A fast protection scheme is devised for distribution networks with loop-based structure based on the deployment of auxiliary DOCRs.

3) Auxiliary relays are optimally placed to relax the most severe constraint without imperiling reliability.

4) To avoid the compromising of the compatibility curves, multi-point coordination approach is employed.

5) Remarkable reduction in overall times of relay tripping is achieved.

The proposed scheme demonstrates a mixed-integer non-linear programming fashion which is solved by particle swarm optimization (PSO) algorithm. Detailed simulation studies are carried out to verify the performance of the proposed scheme.

This paper has been structured in the following way. Section II describes the problem by an illustration-based analysis. Proposed protection scheme is prepared in Section III. Section IV presents the problem formulation. The obtained results are discussed in Section V. Finally, Section VI draws the conclusion.

II. PROBLEM DESCRIPTION: ILLUSTRATION-BASED ANALYSIS

In this section, an illustration-based analysis is carried out to show that DOCRs in chains of loop-based networks stand as an obstacle to follow fast-response protection. Figure 1 shows a simple 3-bus loop-based test system to investigate the mentioned inefficiency. In this network, the pairs of relays (R5, R1), (R1, R3), and (R3, R5) are in a series at chain 1 and the pairs of relays (R2, R6), (R4, R2), and (R6, R4) are in a series at chain 2. Assume that all the lines, generators, loads, and feeders are the same. Consequently, the associated power flow in the lines and the short-circuit capacity in the same points of the lines would be the same, e.g., points A, B, and C. As a simple solution, if the pickup current of DOCRs I_p is considered the same, it would be impossible to satisfy coordination tasks among the relays. For clarity, consider the coordination of relays pertains to the direction indicated in Fig. 1, in which the relays are colored green, and are directional. Therefore, the chains are in opposite directions. The direction of each arrow is from a backup relay to the corresponding primary one. Therefore, arrow directions are from R3 to R1, R5 to R3, and R1 to R5 in chain 1. Likewise, arrow directions are from R2 to R4, R4 to R6, and R6 to R2 in chain 2. Therefore, for a projected fault at point A, R1 should operate as the primary relay

which is backed up by R3.

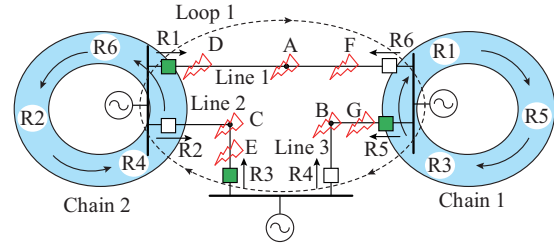


Fig. 1. Simple 3-bus loop-based test system.

Hence, to satisfy critical time interval CTI between these relays, time-current characteristic of R3 must be placed above that of R1, which is shown in Fig. 2.

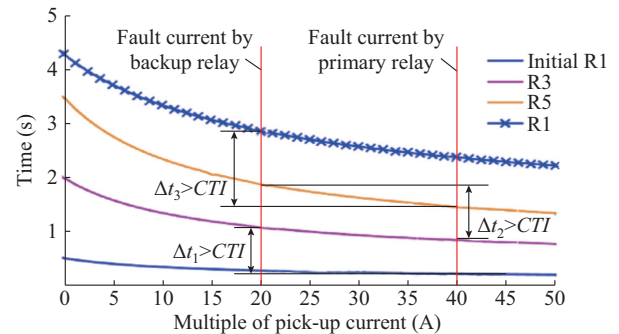


Fig. 2. Time-current characteristics of relays in chain 1.

Due to the assumption mentioned above, for faults at points A, B, and C, all pairs of relays experience the same fault currents. Therefore, for a fault injected at point C, R3 should operate as the primary relay which is backed up by R5. Later, to guarantee selectivity task between these relays, time-current characteristic of R5 must be placed above that of R3 as shown in Fig. 2. Under the same circumstance, R1 should be placed above R5. However, the characteristic of R1 is under R3. Likewise, R3 is under R5. Therefore, it is impossible for the characteristic of R1 to be in two different places at once. Away from the critical condition, the coordination among relays will be possible because of two reasons. Firstly, in practical networks, fault currents are different in coordination points. Secondly, it is possible to choose different I_p for relays. However, this kind of protection scheme brings three drawbacks. Firstly, relay coordination is impossible for the networks with the close feature to the explained network. Secondly, it poses higher I_p for relays, which does not offer a fast-response protection. Furthermore, the increase in I_p of relays will decrease the sensitivity. Thirdly, a time-current characteristic is provided. This can be under a characteristic for a specific fault current and over another characteristic for another fault current, which results in curve crossing. Curve crossing imperils the coordination of relays in other points along each line, which is illustrated in Fig. 3. In this figure, zone 1 is associated with the fault at point D. Likewise, zone 2 is associated with the fault at point E. Moreover, zone 3 is just considered to show curve crossing in mid-point faults at point A. As can be seen, R1 is under R3 in zone 1, and R5 is under R1 in zone 2. How-

ever, R1 has two intersections with R3 and R5 in zone 3. Therefore, by changing the fault point from near-end (D) to mid-point (A) or far-end (F), selectivity task is not satisfied. Furthermore, to provide such characteristic, it is necessary to increase the slope of the curve by increasing time dial setting *TDS* which ends in higher tripping time for relays. To guarantee the selectivity in this situation, it is necessary to increase the coordination points which augment the complexity of coordination problem [14]. Therefore, a powerful coordination approach will be supportive in minimizing the tripping time for relays.

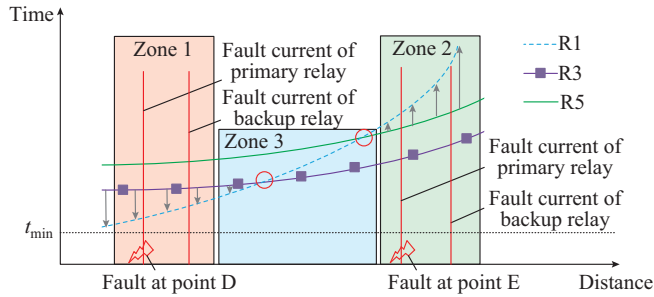


Fig. 3. Curve crossing in coordination process.

III. PROPOSED SCHEME

In this section, the proposed protection scheme for loop-based distribution networks is explained. The proposed scheme relies on auxiliary DOCRs. These relays are deployed to break the chains in each loop. Each chain requires one auxiliary relay. Hence, each loop requires two auxiliary DOCRs. Figure 4(a) demonstrates the 3-bus distribution test system with auxiliary relays. The auxiliary DOCRs are identified by AR1 and AR2 which are deployed here to break the chain 1 and chain 2, respectively. Assume that AR1 is placed between R1 and R5 which protects on the reverse side of R6. AR2 is placed between R2 and R6 which protects on the reverse side of R1. In case of the conventional scheme, R2 is the primary relay and R6 is the backup one for a fault at point C. In the proposed scheme, different pair of relays are assigned. During the fault at the same point, R2 is the primary relay which is backed up with AR2. Similarly, during the fault at point B, R5 is the primary relay which is backed up with AR1. AR1 and AR2 relax the constraints associated with the pairs of relays (R5, R1) and (R2, R6), respectively. Furthermore, the proposed scheme targets the most effective constraints to reduce the complexity of the problem. Therefore, auxiliary relays are optimally placed during the coordination process.

In the proposed scheme, by employing auxiliary DOCRs, there are some relays with two backups. By considering the example mentioned above, after deploying AR1 and AR2, R2 and R5 face with two backup relays. R6 and AR2 can play the backup role for R2. And on the other side, R1 and AR1 can play backup role for R5. Conventional relays are blocked and the newly added auxiliary relays are coordinated with primary relays. Therefore, to avoid any misoperation of the conventional backups, low-bandwidth communication links are considered among the conventional pairs of relays.

When the primary relay detects any fault, it sends a blocking signal to the conventional backup relay. For the injected faults at line 3, e.g., point B, R5 sends the blocking signal to R1. Consequently, R1 will not act for the faults at line 3. Likewise, during the faults at line C, R6 sends the blocking signal to R2. Consequently, the coordination constraints between R2 and R6 as well as between R1 and R5 are relaxed. Consequently, the proposed scheme needs low-bandwidth communication links among these relays to prevent misoperation by blocking the conventional backup relays as shown in Fig. 4(a) and (c).

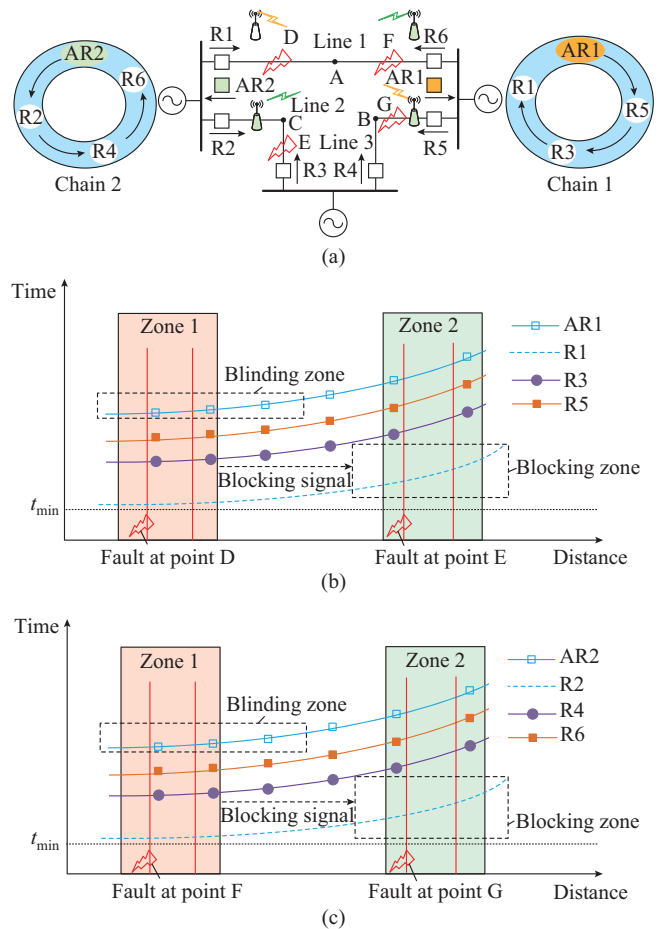


Fig. 4. Protection scheme and relay characteristics. (a) Proposed protection scheme on 3-bus system. (b) Relay characteristics in chain 1. (c) Relay characteristics in chain 2.

Hence, the proposed approach will be able to maintain the achieved reduction in the tripping time of relays while satisfying the requirements of protection coordination. Note that in the case of failures in communication links, the primary relay is not affected and the protection scheme clears the fault in a timely manner. In a more severe case, the communication link might be lost and the primary relay might fail to operate due to a malfunction. However, either the auxiliary relay or conventional backup can successfully clear the fault. And the fault clearance would not be imperiled which preserves reliable fault isolation. Figure 4(b) facilitates the understanding of the communication link arrangements between the auxiliary and conventional DOCRs. For faults at

first zone 1 (point D), R1 clears the fault and AR1 is blind. However, for a fault at zone 2 (point E), AR1 clears the fault and R1 is blocked. The proposed scheme can be implemented on the networks with the close feature to the worst situations of the network, which has been explained previously. Moreover, the time-current characteristic of R1 does not need to be at two places at once, which reduces the probability of curve crossing and helps to fast clear the faults. Finally, the proposed scheme alleviates the complexity of the problem and helps to further reduce the tripping time of relays. The conducted study attempts to relax one constraint in each chain to simplify the optimization space and provide more flexibility. Therefore, each chain requires one auxiliary relay to relax the most severe constraint. Thereby, two auxiliary relays are required in each loop of the network.

The auxiliary DOCRs must be optimally placed in the network. Optimal placement of auxiliary relays entails employing some binary variables. The number of binary variables is equal to the number of pairs of relays. To explain the problem of optimal placement of auxiliary relays, an illustration-based example is presented. Consider that AR1 is the auxiliary relay to break chain 1 in Fig. 1. In this case, there are three scenarios depicted in Fig. 5.

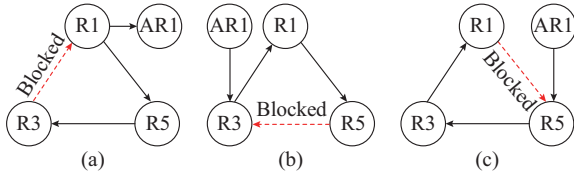


Fig. 5. Breaking chain 1 in different scenarios. (a) Scenario 1. (b) Scenario 2. (c) Scenario 3.

Figure 5(a)-(c) shows the scenarios when AR1 is the backup relay for R1, R3, and R5, respectively. In scenario 1, the selectivity constraint associated with the pair of relay (R1, R3) is relaxed and a new constraint is established for the pair of relay (R1, AR1). Likewise, in scenarios 2 and 3, the selectivity constraints associated with the pairs of relays (R3, R5) and (R5, R1) are relaxed, and new constraints are established for the pairs of relays (R3, AR1) and (R5, AR1). Therefore, three binary variables $L_{ax1,1}$, $L_{ax1,2}$, and $L_{ax1,3}$ are considered for locating AR1 and identifying associated constraints. Thereby, all the conventional selectivity constraints multiply these variables as:

$$(1 - L_{ax1,1})(t_3 - t_1 - CTT) \geq 0 \quad (1)$$

$$(1 - L_{ax1,2})(t_5 - t_3 - CTT) \geq 0 \quad (2)$$

$$(1 - L_{ax1,3})(t_1 - t_5 - CTT) \geq 0 \quad (3)$$

where t_i is the tripping time of relay i ($i=1,3,5$). The new selectivity constraints are established as:

$$L_{ax1,1}(t_{ax1} - t_1 - CTT) \geq 0 \quad (4)$$

$$L_{ax1,2}(t_{ax1} - t_3 - CTT) \geq 0 \quad (5)$$

$$L_{ax1,3}(t_{ax1} - t_5 - CTT) \geq 0 \quad (6)$$

where t_{ax1} is the tripping time of the auxiliary relay. When $L_{ax1,1}$ is 1, the constraint in (1) is relaxed and the constraint in (4) is selected as the new selectivity constraint. Therefore,

the mentioned scheme in the scenario 1 is supported. Moreover, when $L_{ax1,2}$ and $L_{ax1,3}$ are 1, the mentioned schemes in scenarios 2 and 3 are supported. Note that one of these variables is able to be 1. Consequently, the summation of the binary variables has to be 1, which is presented as:

$$L_{ax1,1} + L_{ax1,2} + L_{ax1,3} = 1 \quad (7)$$

The optimization algorithm searches different scenarios and offers the solution with the minimum tripping time for relays. And the optimal locations of auxiliary relays are identified. The proposed scheme can be perused by standard coordination strategy and user-defined coordination strategy. The tripping time of an overcurrent relay is formulated by:

$$t = \frac{TDS \cdot \alpha}{\left(\frac{I_{sc}}{I_p}\right)^\beta - 1} \quad (8)$$

where I_{sc} is the fault current which is seen by the relay; and α and β are coefficients. Typically, TDS and I_p are optimally determined in overcurrent relay, namely standard coordination strategy. To extend the flexibility of overcurrent relay, α and β are also optimized through the coordination process, namely user-defined coordination strategy. In this paper, the proposed scheme is assisted with both the mentioned coordination strategies.

IV. PROBLEM FORMULATION

In the standard coordination strategy, the variable sets include TDS and I_p . Therefore, the coordination problem aims to optimally determine TDS and I_p . In user-defined coordination strategy, α and β are also optimally determined. The final aim is to minimize the overall tripping time of relays which is declared in (9).

$$\min T = \sum_{f \in F} \left[\sum_{i \in I} (t_{i,f} + \sum_{s \in S} t_{i,s,f}) + G \right] \quad (9)$$

where f , i , and s are the indices of fault points, all primary relays, and backup relays, respectively; F , I , and S are the sets of fault points, all primary relays, and backup relays, respectively; and G is the penalty value for violations. There are two kinds of backup relays, i.e., conventional backup relay and auxiliary relay, which are indicated by B and AX , respectively.

$$b \in B \quad (10)$$

$$ax \in AX \quad (11)$$

where B and AX are the sets of conventional backup relays and auxiliary relays, respectively. The union and closure of these sets should satisfy:

$$AX \cup B = S \quad (12)$$

$$AX \cap B = \emptyset \quad (13)$$

$$AX \cap I = \emptyset \quad (14)$$

$$B \subseteq I \quad (15)$$

The tripping time of primary relay i (t_i) for a fault at point f is:

$$t_{i,f} = \frac{TDS_i \cdot \alpha_i}{\left(\frac{I_{sc,i,f}}{I_{Pi}}\right)^{\beta_i}} - 1 \quad i \in I, f \in F \quad (16)$$

The tripping time of conventional and auxiliary backup DOCRs is defined by (17) and (18), respectively.

$$t_{b,f} = \frac{TDS_b \cdot \alpha_b}{\left(\frac{I_{sc,b,f}}{I_{Pb}}\right)^{\beta_b}} - 1 \quad b \in B, f \in F \quad (17)$$

$$t_{ax,f} = \frac{TDS_{ax} \cdot \alpha_{ax}}{\left(\frac{I_{sc,ax,f}}{I_{Pax}}\right)^{\beta_{ax}}} - 1 \quad ax \in AX, f \in F \quad (18)$$

The coordination constraints should be carefully satisfied in reliable and accurate protection schemes. In this manner, selectivity constraints should satisfy *CTI* among all pairs of relays. These constraints are denoted by (19) and (20).

$$(1 - L_{ax,k})(t_{b,f,k} - t_{i,k,f} - CTI) \geq 0 \quad i \in I, b \in B, f \in F, k \in K \quad (19)$$

$$L_{ax,k}(t_{ax,f,k} - t_{i,k,f} - CTI) \geq 0 \quad i \in I, b \in B, f \in F, k \in K, ax \in AX \quad (20)$$

where k is the pair of relays; K is the set of all pairs of relays; $t_{ax,f,k}$ is the tripping time of auxiliary relay in pair of relay k during the fault at f ; $t_{b,f,k}$ is the tripping time of backup relay in pair of relay k during the fault at f ; and $L_{ax,k}$ is the binary variable to relax the selectivity constraint associated with auxiliary relay ax in pair of relay k . This binary variable helps to optimally locate the auxiliary DOCRs and identifies the new selectivity constraint. These statements are the main running constraints to prevent any miscoordination. As mentioned above, the summation of binary variables should be 1 in each chain.

$$\sum_{ax \in AX} \sum_{k \in C_j} L_{ax,k} = 1 \quad j \in J \quad (21)$$

where j is the indice of chains; J is the set of all chains; and C_j is the set that includes the pairs of relays in the chain j which is governed in (22).

$$C_j \subseteq K \quad j \in J \quad (22)$$

To prevent double relaxation among pairs of relays, the following constraint should be included:

$$C_j \cap C_{j+1} = \emptyset \quad (23)$$

The other technical constrains regarding the relay coordination process are as:

$$TDS_{\min} \leq TDS_i \leq TDS_{\max} \quad i \in I \quad (24)$$

$$TDS_{\min} \leq TDS_{ax} \leq TDS_{\max} \quad ax \in AX \quad (25)$$

$$I_{P,\min} \leq I_{Pi} \leq I_{P,\max} \quad i \in I \quad (26)$$

$$I_{P,\min} \leq I_{Pax} \leq I_{P,\max} \quad ax \in AX \quad (27)$$

Constraints (24)-(27) are the main basis for extracting the required settings of standard coordination strategies. In user-defined coordination strategies with non-standard inverse-time characteristics, α and β are also included in the optimization process. These coefficients are defined as the optimi-

zation variables and associated constraints are elaborated by (28)-(31):

$$\alpha_{\min} \leq \alpha_i \leq \alpha_{\max} \quad i \in I \quad (28)$$

$$\alpha_{\min} \leq \alpha_{ax} \leq \alpha_{\max} \quad ax \in AX \quad (29)$$

$$\beta_{\min} \leq \beta_i \leq \beta_{\max} \quad i \in I \quad (30)$$

$$\beta_{\min} \leq \beta_{ax} \leq \beta_{\max} \quad ax \in AX \quad (31)$$

Protection system needs to meet the constraints (32)-(34) to assure the stability and security.

$$t_{\min} \leq t_i \leq t_{\max} \quad i \in I \quad (32)$$

$$t_{\min} \leq t_{i,b} \leq t_{\max} \quad i \in I, b \in B \quad (33)$$

$$t_{\min} \leq t_{i,ax} \leq t_{\max} \quad i \in I, ax \in AX \quad (34)$$

V. TEST SYSTEM DESCRIPTION, NUMERICAL STUDY AND VERIFICATION

A. Testbed

Extensive numerical studies are considered to assess the effectiveness of the proposed scheme in optimal protection coordination problem. P. M. Anderson 9-bus system is considered as the testbed to verify the proposed protection scheme. The single line diagram of this system is shown in Fig. 6(a).

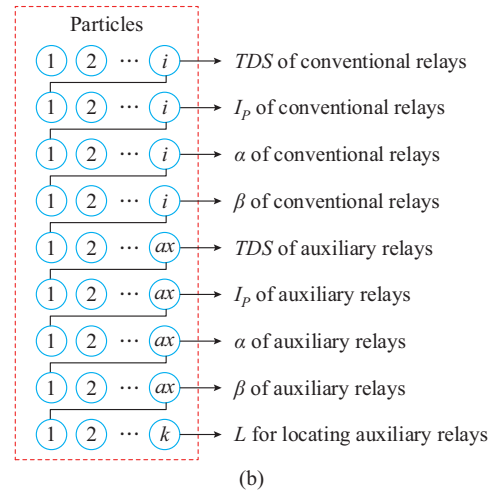
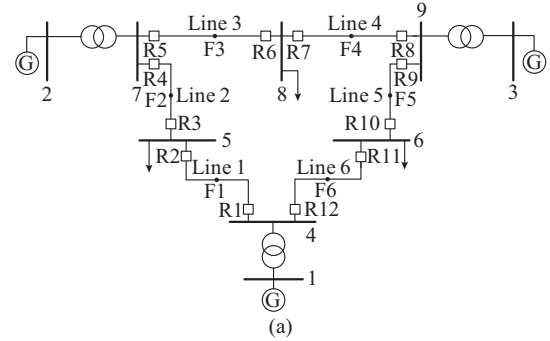


Fig. 6. Relays. (a) Locations on 9-bus test system. (b) Variable set.

Detailed data of the system are also given in [20]. The system is equipped with 12 DOCRs, modeled in DIGSI-

LENT PowerFactory 14.3.1, and analyzed through different case studies. The coordination process is performed based on bolted 3-phase faults. Typically, CTI takes a value between 0.2 and 0.5 s [14]. In this paper, CTI is considered to be 0.3 s. The minimum and maximum I_p will depend on the load currents and short-circuit levels of the system. It is considered between $1.1I_{load,max}$ and $1.5I_{load,max}$, $I_{load,max}$ is the maximum load current. TDS could take a value between 0.1 and 3. Regarding standard time inverse characteristics, α_{min} and β_{min} are 0.14 and 0.02, respectively, whereas α_{max} and β_{max} are assigned as 13.5 and 1, respectively [21]. Moreover, t_{min} and t_{max} for relays are assumed as 0.1 and 2.5 s, respectively [14].

Figure 6(b) shows the form of variable set. As can be seen, binary variables $L_{ax,k}$ are included in the variable set as a particle which determines the location of corresponding auxiliary relay in the proposed scheme. Moreover, TDS_{ax} , $I_{p,ax}$, α_{ax} , and β_{ax} are also included in the variable set as other particles to adjust auxiliary relays. By searching and updating these particles, PSO algorithm aims to find a proper solution with lower tripping time for relays. The method of searching and updating particle by PSO is presented in [25]. The lower- and upper-side values of the settings associated with auxiliary relays are the same as the conventional relays.

B. Numerical Results

Two scenarios are considered to verify the performance of the proposed scheme. In the first scenario, relays are coordinated with the conventional coordination strategy. Therefore, standard inverse characteristics are adopted for DOCRs. In this scenario, TDS and I_p of DOCRs are optimally determined. In the second scenario, the user-defined coordination strategy is followed based on numerical relays. In addition to the conventional settings, time-current characteristics of relays are also optimized in the second scenario. Therefore, the variable set includes TDS , I_p , α , and β .

1) First Scenario

In this scenario, all of the relays are considered as conventional DOCRs. As mentioned above, the conventional coordination process aims to determine TDS and I_p . In this scheme, standard values are assigned to α and β . Here, the obtained optimal results are given in Table I. The tripping time of DOCRs is listed in Table II. These values are derived for the faults located at F1-F6. The total tripping time of the primary and backup relays is 17.8430 s. Additionally, the average and variance of the tripping time is also given in Table II. Selectivity constraints are properly satisfied, as listed in Table II.

The 9-bus test system has one loop. Hence, it involves two chains which are shown in Fig. 7(a). The settings of conventional and auxiliary relays are determined, and the auxiliary relays are also optimally placed. The 9-bus test system requires two auxiliary relays. In this scenario, AR1 is placed beside R2 to relax the constraint between R1 and R3, and the location of AR1 is shown in Fig. 7(b). AR1 and R2 are in opposite directions. Moreover, AR2 is placed beside R7 to relax the constraint between R8 and R6, and the location of AR2 is shown in Fig. 7(c). AR2 and R7 are in opposite directions, too. Figure 7(d) shows the broken chains.

TABLE I
OPTIMAL RESULTS FOR RELAYS ON 9-BUS TEST SYSTEM BASED ON CONVENTIONAL SCHEME

Relay No.	TDS (s)	I_p (kA)	Relay No.	TDS (s)	I_p (kA)
1	0.2168	0.1400	7	0.2120	0.0954
2	0.1126	0.1811	8	0.3290	0.0650
3	0.1000	0.2276	9	0.1862	0.1694
4	0.1312	0.2617	10	0.1110	0.1987
5	0.2111	0.2123	11	0.1479	0.1203
6	0.1046	0.2438	12	0.2776	0.0856

TABLE II
TRIPPING TIME OF RELAYS FOR DIFFERENT FAULTS BASED ON PRESENTED SETTINGS

Fault location	Operation time of relays (s)	
	Primary	Backup
F1	R1: 0.5899	R11: 0.8899
	R2: 0.5322	R4: 0.8322
F2	R3: 0.6161	R1: 0.9277
	R4: 0.4311	R6: 0.7396
F3	R5: 0.6879	R3: 0.9879
	R6: 0.5535	R8: 0.8535
F4	R7: 0.5991	R5: 0.8991
	R8: 0.7309	R10: 1.0309
F5	R9: 0.6417	R7: 0.9417
	R10: 0.5147	R12: 0.8147
F6	R11: 0.5729	R9: 0.8964
	R12: 0.6297	R2: 0.9297
Total tripping time (s)	7.0997	10.7433

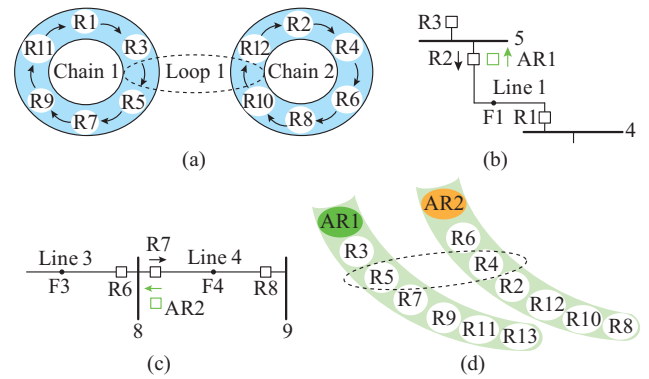


Fig. 7. Chains and location of auxiliary relays. (a) Initial chains. (b) Location of AR1. (c) Location of AR2. (d) Broken chains.

Table III points out the optimal settings of the conventional and auxiliary relays. The tripping time of relays, average, and variance of them are listed in Table IV. The total tripping time of relays is 14.7076 s, which shows a considerable reduction of around 17.5%. Due to different fault currents experienced by relays, the maximum load current, the situation of backup relays, the obtained reductions are different for different relays. The tripping time of R8 is reduced by 0.8 s though the tripping time of R7 is reduced by 0.12 s.

TABLE III
OPTIMAL RESULTS FOR RELAYS ON 9-BUS TEST SYSTEM BASED ON
PROPOSED SCHEME

Relay No.	TDS (s)	I_p (kA)	Relay No.	TDS (s)	I_p (kA)
1	0.1000	0.1265	8	0.1000	0.0649
2	0.1198	0.1586	9	0.1344	0.1779
3	0.1000	0.2178	10	0.1000	0.1661
4	0.1139	0.2971	11	0.1003	0.1105
5	0.1860	0.2075	12	0.2464	0.0828
6	0.1151	0.2079	AR1	0.1911	0.1599
7	0.1627	0.1058	AR2	0.3247	0.0649

TABLE IV
TRIPPING TIME OF RELAYS FOR DIFFERENT FAULTS BASED ON OPTIMIZED
SETTINGS

Fault location	Operation time of relays (s)	
	Primary	Backup
F1	R1: 0.2613	R11: 0.8926
	R2: 0.5181	R4: 0.8527
F2	R3: 0.5926	AR1: 0.9293
	R4: 0.3988	R6: 0.8181
F3	R5: 0.5994	R3: 0.7808
	R6: 0.5418	AR2: 0.6988
F4	R7: 0.4808	R5: 0.7752
	R8: 0.2221	R10: 0.8418
F5	R9: 0.4752	R7: 0.6704
	R10: 0.4129	R12: 0.7476
F6	R11: 0.3704	R9: 0.5613
	R12: 0.5527	R2: 0.7129
Total tripping time (s)	5.4261	9.2815

2) Second Scenario

At the outset, all the relays are coordinated based on the user-defined strategy without using auxiliary relays. In this strategy, coupled with TDS and I_p , the parameters α and β in (8) are also included in the variable sets. These variables help to sweep the time-current page better than before. Therefore, more time-current characteristics are available for DOCRs by including these variables in the optimization process. Here, the obtained settings are given in Table V. Furthermore, based on these settings, the total tripping time of relays is 10.62 s. As can be seen, employing user-defined coordination strategy offers lower tripping time for relays.

Like the previous scenario, the auxiliary relays are deployed to improve quality metrics of the protection coordination in looped structure networks based on user-defined approach. After executing the proposed scheme based on user-defined coordination strategy, the optimized settings for all relays and auxiliary relays are presented in Table VI. In this case, the optimal place for AR1 is between R4 and R6, in the reverse direction of R5. Moreover, the optimal place for AR2 is between R4 and R6, in the reverse direction of R8. Additionally, the total tripping time of relays in this case is 8.3 s, which shows a reduction of around 21.84%. This shows the superiority of the proposed scheme in decreasing trip-

ping time of relays in loop-based networks.

TABLE V
OPTIMAL RESULTS FOR RELAYS ON 9-BUS TEST SYSTEM BASED ON
CONVENTIONAL USER-DEFINED STRATEGY

Relay No.	TDS (s)	I_p (kA)	α	β
1	0.1281	0.1580	7.5765	0.6262
2	0.2508	0.1914	1.9936	0.8032
3	0.2375	0.2453	2.4743	0.9748
4	0.1721	0.2599	6.0726	0.9804
5	0.1623	0.2200	3.2781	0.4182
6	0.1012	0.2431	7.3380	0.9856
7	0.2442	0.1001	5.4102	0.7519
8	0.2031	0.0782	7.2360	0.5103
9	0.2057	0.1883	3.3061	0.5930
10	0.1747	0.1895	5.0958	0.9906
11	0.1917	0.1074	7.0895	0.9549
12	0.5783	0.0915	8.0303	0.9927

TABLE VI
OPTIMAL RESULTS FOR RELAYS ON 9-BUS TEST SYSTEM BASED ON
PROPOSED USER-DEFINED STRATEGY

Relay No.	TDS (s)	I_p (kA)	α	β
1	0.4426	0.1472	3.3400	0.8856
2	0.4022	0.1767	1.5160	0.8770
3	0.2846	0.2290	1.4184	1.0000
4	0.6114	0.2671	1.5054	0.9419
5	0.1558	0.2404	3.4027	0.9296
6	0.6647	0.2384	1.1786	1.0000
7	0.9395	0.1044	1.6882	0.9057
8	0.9653	0.0782	0.8196	0.7621
9	0.4027	0.1930	2.8620	0.8844
10	0.3183	0.1896	1.5278	1.0000
11	0.4903	0.1090	2.0434	0.8926
12	1.0039	0.0928	2.1644	0.7973
AR1	0.2906	0.2101	4.4232	0.8789
AR2	0.1891	0.0649	3.6911	0.3788

C. Result Validation

As a multi-source distribution network, IEEE 14-bus testbed is employed to assess the scalability of the proposed scheme. The single-line diagram of this testbed is shown in Fig. 8. This system includes 16 DOCRs, 22 pairs of relays, 6 synchronous-based DGs, and 2 loops. Detailed data of an IEEE 14-bus testbed can be found in [26]. Moreover, the size and locations of DGs are chosen based on the planning in [26]. The coordination process is performed based on the conventional and proposed schemes. In both cases, standard inverse characteristics are adopted. Table VII shows the obtained results associated with the conventional scheme. Based on these settings, the total tripping time of relays is 78.03 s. Likewise, the obtained results associated with the proposed scheme is listed in Table VIII. In this case, the total tripping time of relays is 48.8 s, which shows a reduction of around 37.5%. Moreover, the solution vector includes

AR1, AR2, AR3, and AR4. These auxiliary relays are located beside and in reverse direction of R3, R4, R5, and R6, respectively, which are highlighted in green color in Fig. 8.

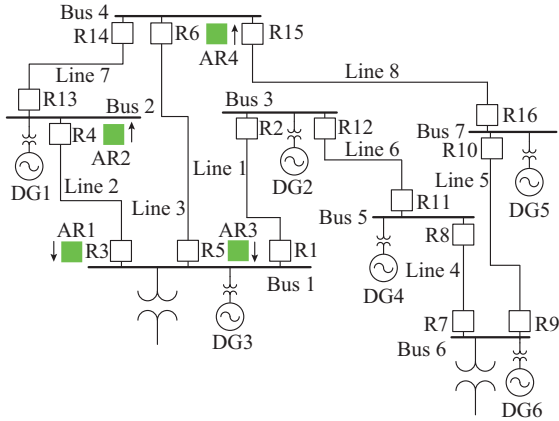


Fig. 8. Single-line diagram of distribution system for an IEEE 14-bus test-bed.

TABLE VII
OPTIMAL RESULTS FOR RELAYS ON 14-BUS TEST SYSTEM BASED ON CONVENTIONAL SCHEME

Relay No.	TDS (s)	I_p (kA)	Relay No.	TDS (s)	I_p (kA)
1	0.5228	0.1995	9	0.3997	0.2520
2	0.2942	0.1995	10	0.2823	0.2394
3	0.4352	0.1706	11	0.4707	0.1020
4	0.1000	0.1474	12	0.5172	0.1020
5	0.3510	0.4695	13	0.4930	0.0435
6	0.1141	0.4695	14	0.2784	0.0435
7	0.5237	0.1680	15	0.4268	0.1470
8	0.3929	0.1232	16	0.3830	0.1470

TABLE VIII
OPTIMAL RESULTS FOR RELAYS ON 14-BUS TEST SYSTEM BASED ON PROPOSED SCHEME

Relay No.	TDS (s)	I_p (kA)	Relay No.	TDS (s)	I_p (kA)
1	0.3170	0.1995	11	0.3633	0.1020
2	0.2230	0.1612	12	0.2674	0.1020
3	0.1000	0.1474	13	0.2743	0.0422
4	0.1000	0.1474	14	0.2784	0.0435
5	0.2109	0.4695	15	0.1000	0.1078
6	0.1000	0.3777	16	0.1000	0.1078
7	0.4295	0.1680	AR1	0.1000	0.1470
8	0.1576	0.1232	AR2	0.2960	0.1470
9	0.1000	0.1848	AR3	0.2818	0.3443
10	0.2655	0.1994	AR4	0.4256	0.3443

Moreover, [23] and [24] conduct studies on developing a protection scheme to meet transient stability constraints in active distribution systems. Furthermore, the effect of other protection strategies such as distance relay and deployment of wide-area protection [25] needs to be assessed to end in a pertinent protection scheme.

VI. CONCLUSION

This study aims to tackle fast-response overcurrent relay in active distribution networks with loop-based structure. DOCRs are in chains with different loops, which restricts minimal tripping time for relays. Afterward, a fast protection scheme is presented which breaks the chains in the corresponding loops. The most effective constraint associated with each chain is relaxed during the coordination process by using the auxiliary DOCRs. These relays are also optimally adjusted and placed. The proposed method is modeled based on conventional and user-defined coordination strategies. The following points are observed as the major conclusions:

- 1) The conventional scheme for loop-based distribution networks is in line with higher tripping time for DOCRs. Therefore, it might result in disconnections of DG or feeder.
- 2) The coordination of DOCRs in different chains is highlighted as one of the most important obstacles in obtaining fast-response protection.
- 3) The deployment of auxiliary relays is helpful in breaking the chains. Furthermore, it contributes to faster protection.
- 4) The deployed auxiliary DOCRs should be adjusted and optimally placed. Therefore, to end in optimal set-points for DOCRs, a proper model is launched which satisfies the constraints associated with the selectivity of DOCRs and placement of auxiliary relays.
- 5) Moreover, by employing the proposed method with both conventional and user-defined coordination strategies, the tripping time of relays decreases more than 17% and 22%, respectively.

The conducted survey is still an open topic to be explored. The consideration of configuration variations for the network in the coordination process would be the subject of future research work.

REFERENCES

- [1] S. Teimourzadeh, S. F. Aminifar, M. Davarpanah *et al.*, "Macroprotections for microgrids: toward a new protection paradigm subsequent to distributed energy resource integration," *IEEE Industrial Electronics Magazine*, vol. 10, no. 3, pp. 6-18, Sept. 2016.
- [2] M. Alipour, M. S. Teimourzadeh, and H. Seyedi, "Improved group search optimization algorithm for coordination of directional overcurrent relays," *Swarm and Evolutionary Computation*, vol. 23, pp. 40-49, Aug. 2015.
- [3] R. Khezri, S. Golshannavaz, S. Shokoohi *et al.*, "Toward intelligent transient stability enhancement in inverter-based microgrids," *Neural Computing and Applications*, vol. 30, no. 9, pp. 2709-2723, Nov. 2018.
- [4] S. Teimourzadeh, F. Aminifar, and M. Davarpanah, "Microgrid dynamic security: challenges, solutions and key considerations," *The Electricity Journal*, vol. 30, no. 4, pp. 43-51, May 2017.
- [5] R. E. Albrecht, M. J. Nisja, W. E. Feero *et al.*, "Digital computer protective device co-ordination program I-general program description," *IEEE Transactions on Power Apparatus and Systems*, vol. 83, no. 4, pp. 402-410, Apr. 1964.
- [6] Y. Li, D. Shi, and X. Duan, "An integrated power system relay coordination software," in *Proceedings of PES Summer Meeting*, Vancouver, Canada, Jul. 2001, pp. 1315-1318.
- [7] B. Chattopadhyay, M. S. Sachdev, and T. S. Sidhu, "An on-line relay coordination algorithm for adaptive protection using linear programming technique," *IEEE Transactions on Power Delivery*, vol. 11, no. 1, pp. 165-173, Jan. 1996.
- [8] P. P. Bedekar, S. R. Bhide, and V. S. Kale, "Optimum coordination of overcurrent relay timing using simplex method," *Electric Power Com-*

- ponents and Systems, vo. 38, no. 10, pp. 1175-1179, Jul. 2010.
- [9] H. Bouchekara, M. Zellagui, M. A. Abido *et al.*, "Optimal coordination of directional overcurrent relays using a modified electromagnetic field optimization algorithm," *Applied Soft Computing*, vol. 54, pp. 267-283, May 2017.
- [10] R. Thangaraj, M. Pant, and K. Deep, "Optimal coordination of overcurrent relays using modified differential evolution algorithms," *Engineering Applications of Artificial Intelligence*, vol. 23, no. 5, pp. 820-829, Aug. 2010.
- [11] M. N. Alam, B. Das, and V. Pant, "An interior point method based protection coordination scheme for directional overcurrent relays in meshed networks," *International Journal of Electrical Power & Energy Systems*, vol. 81, pp. 153-164, Oct. 2016.
- [12] M. N. Alam, B. Das, and V. Pant, "A comparative study of metaheuristic optimization approaches for directional overcurrent relays coordination," *Electric Power Systems Research*, vol. 128, pp. 39-52, Nov. 2015.
- [13] A. J. Urdaneta, H. Restrepo, S. Marquez *et al.*, "Coordination of directional overcurrent relay timing using linear programming," *IEEE Transactions on Power Delivery*, vol. 11, no. 11, pp. 122-129, Jan. 1996.
- [14] R. Mohammadi, H. A. Abyaneh, H. M. Rudsari *et al.*, "Overcurrent relays coordination considering the priority of constraints," *IEEE Transactions on Power Delivery*, vol. 26, no. 3, pp. 1927-1938, Jul. 2011.
- [15] A. Yazdanejadi, M. S. Naderi, G. B. Gharehpetian *et al.*, "Protection coordination of directional overcurrent relays: new time current characteristic and objective function," *IET Generation, Transmission & Distribution*, vol. 12, no. 1, pp. 190-199, Jan. 2018.
- [16] H. C. Kılıçkiran, İ. Şengör, and H. Akdemir, "Power system protection with digital overcurrent relays: a review of non-standard characteristics," *Electric Power Systems Research*, vol. 164, pp. 89-102, nov. 2018.
- [17] S. Teimourzadeh, M. Davarpanah, F. Aminifar *et al.*, "An adaptive auto-reclosing scheme to preserve transient stability of microgrids," *IEEE Transactions on Smart Grid*, vol. 9, no. 4, pp. 2638-2646, Jul. 2018.
- [18] R. Khezri, S. Shokoohi, and S. Golshannavaz, "Intelligent over-current protection scheme in inverter-based microgrids," in *Proceedings of Smart Grid Conference*, Tehran, Iran, Dec. 2015, pp. 53-59.
- [19] A. G. Phadke, P. Wall, L. Ding *et al.*, "Improving the performance of power system protection using wide area monitoring systems," *Journal of Modern Power Systems and Clean Energy*, vol. 4, no. 3, pp. 319-331, Jul. 2016.
- [20] N. Watsn and J. Arrillaga, *Power Systems Electromagnetic Transients Simulation*, London: IEE Power and Energy Series, 2003, pp. 193-198.
- [21] H. C. Kılıçkiran, H. Akdemir, and İ. Şengör, "A non-standard characteristic based protection scheme for distribution networks," *Energies*, vol. 11, no. 5, pp. 1241, May 2018.
- [22] K. E. Parsopoulos and M. N. Vrahatis, "Particle swarm optimization method for constrained optimization problems," in *Intelligent Technologies-Theory and Applications: New Trends in Intelligent Technologies*, Amsterdam: IOS Press, 2002, pp. 214-220.
- [23] S. Golshannavaz, M. Mokhtari, M. Khalilian *et al.*, "Transient stability enhancement in power system with distributed static series compensator (DSSC)," in *Proceedings of 19th Iranian Conference on Electrical Engineering*, Tehran, Iran, May 2011, pp. 1-6.
- [24] L. Miao, J. Fang, J. Wen *et al.*, "Transient stability risk assessment of power systems incorporating wind farms," *Journal of Modern Power Systems and Clean Energy*, vol. 1, no. 2, pp. 134-141, Sept. 2013.
- [25] J. W. Lee, W. K. Kim, J. Han *et al.*, "Fault area estimation using traveling wave for wide area protection," *Journal of Modern Power Systems and Clean Energy*, vol. 4, no. 3, pp. 478-486, Jul. 2016.
- [26] S. Khanbabapour and M. E. H. Golshan, "Synchronous DG planning for simultaneous improvement of technical, overcurrent, and timely anti-islanding protection indices of the network to preserve protection coordination," *IEEE Transactions on Power Delivery*, vol. 32, no.1, pp. 474-483, Feb. 2017.

Amin Yazdanejadi received the B.Sc. degree in electrical engineering from Urmia University, Urmia, Iran, in 2012, the M.Sc. degree in electrical engineering from Amirkabir University of Technology (AUT), Tehran, Iran, in 2014, and Ph.D. (Hons.) degree from Urmia University, Urmia, Iran, in 2018. He is currently an Assistant Professor in the Department of Electrical Engineering, Shahid Rajaee Teacher Training University, Tehran, Iran. His research interests include power system protection, power system automation, and smart grid technologies.

Daryoush Nazarpour received the B.Sc. degree from the Iran University of Science and Technology, Tehran, Iran, in 1982, and the M.Sc. and Ph.D. degrees from University of Tabriz, Tabriz, Iran, in 1988 and 2005, respectively, all in electrical engineering. He is currently a Professor in the Department of Electrical Engineering, Urmia University, Urmia, Iran. His research interests are primarily centered in advanced power electronics and flexible AC transmission systems applications in power systems as well as smart grid technologies.

Vahid Talavat is an Assistant Professor in the Department of Electrical Engineering, Urmia University, Urmia, Iran. His research interest includes power system protection.