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Optimal Placement of Protective and Controlling Devices in Electric Power Distribution Systems: A MIP Model

MILAD IZADI[1], (Student Member, IEEE), AMIR SAFDARIAN[1,2], (Member, IEEE), MOEIN MOEINI-AGHTAIE[1], (Member, IEEE), AND MATTI LEHTONEN[2]

[1]Department of Energy Engineering, Sharif University of Technology, Tehran 11365-11155, Iran
[2]Department of Electrical Engineering and Automation, Aalto University, 15500 Espoo, Finland

Corresponding author: Amir Safdarian (safdarian@sharif.edu)

ABSTRACT This paper presents a mathematical model for simultaneous deployment of protective devices (PDs) and controlling devices (CDs) in distribution networks. The PDs include fuses and reclosers and the CDs are remote controlled switches (RCSs) and manual switches (MSs). The model is to minimize equipment costs as well as sustained and momentary interruption costs. It considers the coordination of fuses and reclosers during temporary faults involving *fuse saving* and *fuse blowing* schemes. The model is in mixed integer programming (MIP) fashion which can be effectively solved with available solvers. The performance of the proposed model is verified through applying it to Bus 4 of Roy Billinton test system and a real-life distribution network. The results reveal the effectiveness of the model in reducing system costs as well as in improving reliability level.

INDEX TERMS Electric power distribution system, fault management, mixed integer programming, power distribution protection, power distribution reliability.

NOMENCLATURE

Indices and Sets:

$i, I^{a/e/o}$	Index and set of all/even/odd fault locations
j, J	Index and set of load points
f, F	Index and set of feeders
k, K	Index and set of customer types
s, S	Index and set of candidate locations
t, T	Index and set of years

Parameters and Constants:

$CIC_{f,s}^{RCS/MS}$	Capital investment and installation costs of RCS/MS in feeder f and location s
$CIC_{f,s}^{Fu/Re}$	Capital investment and installation costs of fuse/recloser in feeder f and location s
$MC_{f,s}^{RCS/MS}$	Maintenance cost of RCS/MS in feeder f and location s
$MC_{f,s}^{Fu/Re}$	Maintenance cost of fuse/recloser in feeder f and location s
$\lambda_{t,f,i}^{p/t}$	Permanent/Temporary failure rate at section i in feeder f at year t
$cdf_{t,f,i,j,k}^{RCS/MS/R}$	Customer damage function for customers with type k at load point j for a fault at section i in feeder f at year t, restored with remote switching/manual switching/repair action
$cdf_{t,f,i,j,k}^{M}$	Customer damage function for customers with type k at load point j for a temporary fault at section i in feeder f at year t caused a momentary interruption
d	Discount rate
$L_{t,f,j,k}$	Load level of customers with type k at load point j in feeder f at year t
$\overline{N}_f^{Re}$	Maximum number of recloser deployments in feeder f
$Budget$	Total budget
$\epsilon, \epsilon'/\zeta, \zeta'$	Small/Large auxiliary constants

Variables and Functions:

C^{eq}	Cost of equipment
C^{int}	Expected total interruption cost

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$C^{CD/PD}$	Cost of CD/PD
$C^{int,p/t}$	Expected interruption cost originated from permanent/temporary faults
$C^{p/t}_{t,f,i,j,k}$	Customer interruption cost for customers with type k at load point j for a permanent/temporary fault at section i in feeder f at year t
$P_{f,i,j}$	Integer variable indicating the number of PDs between the faulted section i and load point j in feeder f
$b_{f,i,j}$	Binary variable indicating if load point j is protected when a fault occurs at section i in feeder f
$Q_{f,i}$	Integer variable indicating the number of reclosers between faulted section i in feeder f and the upstream fuse or the beginning of the feeder
$c_{f,i}$	Binary variable indicating if a temporary fault occurs at section i in feeder f leads to momentary interruption
$X^{RCS/MS}_{f,s}$	Binary variable indicating if RCS/MS is installed on location s in feeder f
$X^{Fu/Re}_{f,s}$	Binary variable indicating if a fuse/recloser is installed on location s in feeder f

I. INTRODUCTION

The majority of service interruptions in power systems are originated from faults in distribution networks [1]. To enhance service reliability, distribution companies (DisCos) usually apply various approaches for reducing frequency and duration of interruptions [2]. Among them, installing protective and controlling devices has caught more attention of DisCos. Protective devices (PDs) such as recloser and fuse reduce the number of interruptions since they protect upstream consumers from downstream faults. In addition, reclosers clear downstream temporary faults, thereby avoiding sustained interruptions. Apart from PDs, controlling devices (CDs) including remote controlled switch (RCS) and manual switch (MS) speed up service restoration via enabling prompt reconfiguring maneuvers. Therefore, PDs, by decreasing interruption frequencies, and CDs, by decreasing interruption durations, can improve reliability level of the system. These devices, although bring numerous advantageous to DisCos, impose significant investment, installation, and maintenance costs. To economically justify the costs, it is necessary to conduct a cost/benefit analysis to achieve the optimal number and location of the devices [3]. This article develops a model for the simultaneous placement of PDs and CDs in a network.

In the literature, various algorithms and mathematical models have been used for CD placement in distribution networks. Among heuristic algorithms, genetic algorithms [4], simulated annealing algorithms [5], ant colony algorithms [6], immune algorithms [7], and particle swarm optimization algorithms [8] were introduced to solve the optimal CD placement problem. Although the heuristic algorithms are easy to implement, they do not necessarily find the global optimal solution since they may get stuck into local optimal solutions. Along with these heuristic algorithms, mathematical optimization models in mixed integer programming (MIP) fashion have been introduced. In [9], the CD placement problem was solved via a MIP model wherein system interruption and RCS costs are minimized as objective. The model was extended to consider the potential impact of earth fault events in [10] and to consider the potential location of switches on both the main feeder and laterals in [11]. To consider annual monetary limits, [12] proposed a multi-stage model to determine the optimal number, location, and installation year of the switches. Due to the remote capability of RCS in prompt isolation in comparison to MS and consequently in improving system reliability, it makes sense to replace some of the installed MSs with RCSs. To consider this issue, [13], [14] proposed RCS placement models to upgrade MSs to RCSs. References [15] and [16] extended the MIP models to consider malfunction probability of the switches. Also, financial risks caused by the stochastic nature of faults and its impacts on the switch placement problem were studied in [17]–[19].

Beside the research focused on the optimal CD placement problem, the optimal placement of PDs has attracted attention of many researchers as well. In [20], [21], binary programming (BP) models have been proposed for PD placement problem such that system average interruption frequency index (SAIFI) is minimized considering the permanent and temporary faults. In [22], [23], non-linear binary programming (NLBP) models were introduced to solve the problem.

Although the reviewed articles provided effective techniques and models for either CD or PD placement problem, but as mentioned before, PDs and CDs play complementary roles in enhancing fault management process. Therefore, it makes sense to consider both PDs and CDs in one problem in order to reach a more effective and economic solution rather than individual placement of the devices. Therefore, some researchers have tried to propose models and algorithms for solving this problem. Among the heuristic techniques, particle swarm optimization algorithms [24], ant colony algorithms [25], and reactive Tabu search algorithms [26] were applied to solve joint PD and CD placement problem. In [27], the authors proposed a mathematical model to determine the location of *fuse blowing* and *fuse saving* fuses by minimizing the combination of the SAIFI and the momentary average interruption frequency index (MAIFI). In [28], [29], non-linear models have been developed for placement of PDs and CDs considering permanent faults. The proposed model in [29] was extended in [30] by considering both temporary and permanent faults. Although [28], [30] considered PDs and CDs in one problem, the proposed models were formulated in mixed integer non-linear programming format which does not necessarily lead to the optimal solution, while our proposed MIP model guarantees finding the global optimum solution.

As described heretofore, most of the reviewed literature proposed effective approaches for either PD or CD placement problem. A few articles developed heuristic approaches and non-linear models for simultaneous placement of PD and CD in distribution networks, but none of them proposed a MIP model. It is worthwhile to mention that the proposed placement problem is a combinatorial and complex optimization problem and solving it using heuristic algorithms which explore only a narrow region of the search space and have a tendency of getting stuck into locally optimal solutions is time-consuming. With this in mind and to find the global optimum solution, as the main contribution of this paper, the optimum placement of PD and CD is meticulously modeled in one problem with MIP formulation which guarantees the global optimum solution. In summary, major contributions of the paper are as follows.

- This paper presents one mathematical model for simultaneous placement of four devices including fuses, reclosers, MSs, and RCSs.
- The impact of temporary and permanent faults on interruption cost and how temporary faults may cause momentary or sustained interruptions is considered.
- The coordination of fuses and reclosers during a temporary fault including *fuse saving* and *fuse blowing* is considered and is linearly formulated in the problem.
- The developed model is in MIP fashion which guarantees convergence to the global optimum solution.

II. METHODOLOGY

As mentioned earlier, PDs and CDs play a key role in improving service reliability. The PDs are useful in decreasing interruption frequencies, and the CDs are helpful in reducing interruption durations. The interruption frequency and interruption duration have a direct impact on customers interruption cost. Therefore, installing PDs has effect on CDs deployment and vice versa. In this regard, this section presents a mathematical model to determine the optimum number and location of PDs and CDs simultaneously. While these equipment can make benefit via reducing customers interruption cost, they impose some costs including investment, installation, and maintenance costs. In this regard, a trade-off between the costs and service reliability is necessary to reach the maximum benefits of the devices deployment. A well-known reliability index is the expected interruption cost to measure the service reliability which is used in this work. The service reliability level of a system improved when expected interruption cost is minimized. Also, its unit is the same as that of the device cost. With this in mind, the problem can be expressed with a single objective where the objective is the summation of the equipment cost and the interruption cost as follows:

$$Minimize\ C^{eq} + C^{int} \tag{1}$$

where C^{eq} and C^{int} are the equipment cost and system interruption cost, respectively. In (1), The equipment cost consists of the costs of CDs and PDs as follows:

$$C^{eq} = C^{CD} + C^{PD} \tag{2}$$

where the CD cost, C^{CD}, including capital investment, installation, and maintenance costs for RCS and MS is as follows:

$$C^{CD} = \sum_{f\in F}\sum_{s\in S}(X^{RCS}_{f,s}CIC^{RCS}_{f,s} + X^{MS}_{f,s}CIC^{MS}_{f,s}) + \sum_{t\in T}\sum_{f\in F}\sum_{s\in S}\frac{1}{(1+d)^t}(X^{RCS}_{f,s}MC^{RCS}_{f,s} + X^{MS}_{f,s}MC^{MS}_{f,s}) \tag{3}$$

In (3), the first term indicates RCS and MS capital investment and installation costs, and the second one represents present value of maintenance costs. The PD cost, C^{PD}, consisting of fuse and recloser costs is defined as follows:

$$C^{PD} = \sum_{f\in F}\sum_{s\in S}(X^{Fu}_{f,s}CIC^{Fu}_{f,s} + X^{Re}_{f,s}CIC^{Re}_{f,s}) + \sum_{t\in T}\sum_{f\in F}\sum_{s\in S}\frac{1}{(1+d)^t}(X^{Fu}_{f,s}MC^{Fu}_{f,s} + X^{Re}_{f,s}MC^{Re}_{f,s}) \tag{4}$$

According to (3)-(4), capital investment and installation costs as well as maintenance costs depend on the location of equipment. In fact, various factors such as network types, communication infrastructure, and capacity of equipment to name just a few may affect the costs of equipment. Therefore, it makes sense to consider different costs for different candidate locations in networks.

It bears mentioning that, usually, the main goal of utilities is to reach the highest profit of a equipment installation. With this in mind, the profit of device allocation is the reduction of system interruption cost after placement minus the equipment cost. Since the system interruption cost before installing devices is constant, maximization of the net profit is equivalent to minimization of the total system cost in the presence of devices (see (1)).

The interruption cost depends on the customer interruption duration following a fault. Interruptions can be categorized into two main groups involving momentary and sustained interruptions. A report published by Lawrence Berkeley National Lab indicates that momentary interruptions account for about 67% of total system interruptions in the USA [31]. So, it makes sense to consider the impact of temporary faults in the problem. In this regard, in this paper, interruption costs for both types of faults are considered as follows:

$$C^{int} = C^{int,p} + C^{int,t} \tag{5}$$

where

$$C^{int,p} = \sum_{t\in T}\sum_{f\in F}\sum_{i\in I^a}\sum_{j\in J}\sum_{k\in K}\frac{1}{(1+d)^t}\lambda^{p}_{t,f,i}L_{t,f,j,k}C^{p}_{t,f,i,j,k} \tag{6}$$

$$C^{int,t} = \sum_{t\in T}\sum_{f\in F}\sum_{i\in I^a}\sum_{j\in J}\sum_{k\in K}\frac{1}{(1+d)^t}\lambda^{t}_{t,f,i}L_{t,f,j,k}C^{t}_{t,f,i,j,k} \tag{7}$$

In the above expressions, the system interruption costs originated from permanent and temporary faults are determined based on (6) and (7), respectively. In the expressions, the interruption cost depends on failure rate, load level of customers, and the interruption cost imposed on customers following a fault. The failure rate and load level are known and predefined parameters, while customer interruption cost depends on the interruption duration. Also, the interruption duration relies on the network topology, the location of both PDs and CDs, and the time needed for switching and repair actions. It is worthwhile to point that, as aforementioned, PDs affect the failure rate, while CDs influence on the interruption duration. In this paper, the impact of PD installation is modeled via an interruption with duration equal to zero. The impact of permanent faults on system interruption cost is studied firstly, then that of temporary faults is taken into consideration.

A. IMPACT OF PERMANENT FAULTS

To clarify the impact of PDs and CDs on the duration of interruptions, a representative feeder is shown in Figure 1. As can be seen, the feeder feeds n load points and is equipped with a circuit breaker (CB) at the beginning of the feeder. The feeder is also equipped with a tie switch (TS) which enables serving customers from the neighboring feeder in emergency situations. In the figure, candidate locations for installing PDs and CDs are specified in both the main feeder and laterals. For simplicity of notation, the subscript f is dropped in the location of equipment in the figure, i.e., $X_{f,s} \to X_s$. Assume that a permanent fault occurs in section $i \in I^a = \{1, 2, \cdots, 2n\}$ where $I^a = I^e \cup I^o$. According to the numbering strategy in the figure, $i \in I^o$, on the main feeder, is equal to $2j - 1$ where j indicates the first load point located downstream of the faulted section. Likewise, $i \in I^e$, on the lateral, is equal to $2j$ where j specifies the load point in the faulted section. To determine customers affected by the fault, the following expression is formulated.

$$\frac{P_{f,i,j}}{\zeta} - \epsilon \le b_{f,i,j} \le \frac{P_{f,i,j}}{\zeta} + 1 - \epsilon; \quad \forall f \in F, \quad \forall i \in I^a, \ \forall j \in J \tag{8}$$

where $b_{f,i,j}$ is equal to one if there is any PD, either fuses or reclosers, between the faulted section and the load point, zero otherwise. Also, $P_{f,i,j}$ indicates the number of PDs installed between the two. The value of $P_{f,i,j}$ can be mathematically determined as follows:

$$P_{f,i,j} = \sum_{s=s_j}^{s_i} X_{f,s}^{Fu} + \sum_{s=s_j}^{s_i} X_{f,s}^{Re}; \quad \forall f \in F, \ \forall i \in I^a, \ \forall 2j < i \tag{9a}$$

$$P_{f,i,j} = X_{f,s}^{Fu} + X_{f,s}^{Re}; \quad \forall f \in F, \ \forall i \in I^e, \ \forall 2j > i, \ s = s_i \tag{9b}$$

$$P_{f,i,j} = 0; \quad \forall f \in F, \ \forall i \in I^e, \ \forall 2j = i \ \vee \forall i \in I^o, \quad \forall 2j > i \tag{9c}$$

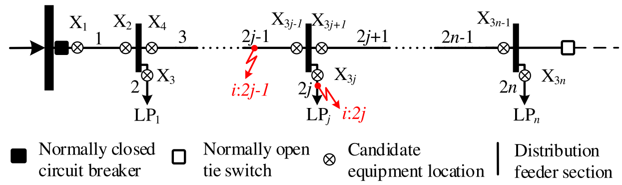

FIGURE 1. **A representative feeder.**

where $X_{f,s}^{Fu}$ and $X_{f,s}^{Re}$ are the binary variables that are equal to one if the associated PD is installed at the indicated location, zero otherwise. Also, s_j and s_i, respectively, indicate the location of the first equipment adjacent to load point j and faulted section i. In (9a), it is assumed that the fault occurs downstream of the load points (i.e., $2j < i$). In this situation, if any PDs exist between the faulted section and load points, the customers connected to the load points do not suffer from interruption, while other customers located downstream of the first PD near the faulted section are interrupted. In (9b), if there is any PD at the beginning of the faulted lateral (i.e., $2j > i, i \in I^e$), customers hosted by downstream load points can be isolated from the fault and remain energized. In (9c), if the fault and load point are at the same section (i.e., $2j = i, i \in I^e$) or the fault occurs upstream of the load point on the main feeder (i.e., $2j > i, i \in I^o$), the customers are interrupted, therefore $P_{f,i,j}$ would be equal to zero. In nutshell, if any PD is available between the faulted section and load points and senses the fault current, the load points do not experience interruption, and consequently their interruption duration would be equal to zero, otherwise the load points should be restored through fault management process to determine the interruption duration.

Fault management process is referred to as the set of actions taken by operators to restore service to as much interrupted customers as and as fast as possible [32]. In this regard, if there is neither recloser nor fuse between the two, three restoration actions involving remote switching, manual switching, and repair actions are applied to re-energize the interrupted customers. It should be mentioned that in this work, it is assumed that the system operator uses a management model to make the best and most reasonable actions using the installed devices [33] and the coordination between different protection devices is perfect.

1) REMOTE SWITCHING ACTION

Even in optimistic situation, the customers can be restored after the time required for remote switching actions. In this regard, if there is any RCS between the faulted section and the load point, the customers connected to the load point can be remotely isolated from the faulted section via opening the RCS. This situation is mathematically formulated as follows:

$$C_{t,f,i,j,k}^{p} \ge cdf_{t,f,i,j,k}^{RCS}(1 - b_{f,i,j}); \quad \forall t \in T, \ \forall f \in F, \ \forall i \in I^a, \quad \forall j \in J, \ \forall k \in K \tag{10}$$

2) MANUAL SWITCHING ACTION

If there is no RCS between the faulted section and load points, the existence of any MS between the two provides an opportunity to restore the customers through manual switching actions. This situation is formulated in (11a)-(11b) as follows:

$$C^{p}_{t,f,i,j,k} \geq cdf^{MS}_{t,f,i,j,k}\left(1-\sum_{s=s_j}^{s_i} X^{RCS}_{f,s}\right)(1-b_{f,i,j}); \quad \forall t \in T, \quad \forall f \in F, \ \forall i \in I^a, \ \forall 2j < i, \quad \forall k \in K \tag{11a}$$

$$C^{p}_{t,f,i,j,k} \geq cdf^{MS}_{t,f,i,j,k}\left(1-\sum_{s=s_i}^{s_j} X^{RCS}_{f,s}\right)(1-b_{f,i,j}); \quad \forall t \in T, \quad \forall f \in F, \ \forall i \in I^a, \ \forall 2j > i, \quad \forall k \in K \tag{11b}$$

where (11a) and (11b) are applied for customers whose connection points are located upstream (i.e., $2j < i$) and downstream (i.e., $2j > i$) of the faulted section, respectively.

3) REPAIR ACTION

If there is neither RCS nor MS between the two, the customers should remain interrupted until the faulted section is repaired. This circumstance is expressed as follows:

$$C^{p}_{t,f,i,j,k} \geq cdf^{R}_{t,f,i,j,k}\begin{pmatrix}1-\sum_{s=s_j}^{s_i} X^{RCS}_{f,s} \\ -\sum_{s=s_j}^{s_i} X^{MS}_{f,s}\end{pmatrix}(1-b_{f,i,j}); \quad \forall t \in T, \quad \forall f \in F, \ \forall i \in I^a, \ \forall 2j < i, \ \forall k \in K \tag{12a}$$

$$C^{p}_{t,f,i,j,k} \geq cdf^{R}_{t,f,i,j,k}\begin{pmatrix}1-\sum_{s=s_i}^{s_j} X^{RCS}_{f,s} \\ -\sum_{s=s_i}^{s_j} X^{MS}_{f,s} \\ -\sum_{s=s_i}^{s_j} X^{Re}_{f,s}\end{pmatrix}(1-b_{f,i,j}); \quad \forall t \in T, \quad \forall f \in F, \ \forall i \in I^a, \ \forall 2j > i, \ \forall k \in K \tag{12b}$$

$$C^{p}_{t,f,i,j,k} \geq cdf^{R}_{t,f,i,j,k}(1-b_{f,i,j}); \quad \forall t \in T, \quad \forall f \in F, \ \forall i \in I^e, \ \forall 2j = i, \ \forall k \in K \tag{12c}$$

where (12a) and (12b) are used for customers located upstream and downstream of the faulted section, respectively. (12c) is considered for customers located in the faulted section (i.e., $2j = i$). Since the customers cannot be isolated from the faulted section in this situation, they should retain interrupted until the repair action is over. It is worthwhile to point that since PDs located between the faulted section and downstream customers (i.e., $2j > i$) cannot sense the fault current, they can be used as a switching device to isolate the customers out of the faulted zone. So, a recloser has the same impact on the reduction of interruption duration as a MS has. This issue is considered in (12b) where a summation associated with the number of reclosers between the faulted section and load point is implemented in the constraint. Needless to mention, according to (9c), when a fault occurs in a load point section, $b_{f,i,j}$ would be equal to zero, and therefore this variable can be removed from (12c).

To better clarify the above-mentioned expressions, consider that a few RCSs are deployed between the faulted section and the upstream load point (i.e., $2j < i$). In this situation, the summation terms associated with RCS in (11a) and (12a) are equal to one or more, which makes the right-hand-side of the constraints equal to zero or less. So, by considering constraints (10), (11a), and (12a), the time required for remote switching action is imposed on the customers hosted by the load point. As another example, assume that a fault occurs upstream of a load point (i.e., $2j > i$). If neither RCS nor MS exists between the faulted section and load point, while any recloser exists between the two, the right-hand-side of constraint (12b) would be equal to zero or a negative value, while constraint (11b) would not. Hence, by taking into consideration constraints (10), (11b), and (12b), the time needed for manual switching action is imposed on the customers connected to the load point. So, the customers experience longer interruption duration in comparison with those restored remotely. Note that, since the recloser, located downstream of the faulted section, cannot sense the fault current, $b_{f,i,j}$ would be equal to zero.

B. IMPACT OF TEMPORARY FAULTS

In this subsection, the impact of temporary faults on system interruption cost is considered. As mentioned in IEEE Standard 1366 [34], interruptions with duration shorter than 5 minutes are considered as momentary interruptions, otherwise they are deemed as sustained interruptions. A temporary fault may cause either a sustained or a momentary interruption based on the coordination of available fuses and reclosers between the faulted section and power sources [35]. The coordination between fuses and reclosers when a temporary fault occurs is divided into two schemes involving *fuse blowing* and *fuse saving* schemes which are discussed and formulated hereinafter. It bears mentioning that the two schemes are linearly formulated in the placement problem. To determine whether a temporary fault leads to a momentary or sustained interruption, the following expression is considered.

$$\frac{Q_{f,i}}{\zeta'} - \epsilon' \leq c_{f,i} \leq \frac{Q_{f,i}}{\zeta'} + 1 - \epsilon'; \quad \forall f \in F, \ \forall i \in I^a \tag{13}$$

In (13), if $Q_{f,i}$ takes zero, $c_{f,i}$ is forced to get zero, which means that the temporary fault causes a sustained interruption. Otherwise, $c_{f,i}$ is equal to one, which implies that the fault leads a momentary interruption. $Q_{f,i}$ represents the number of available fuses and reclosers between the faulted section and the power source. The value of $Q_{f,i}$ depends on the scheme considered for the coordination of reclosers and fuses.

1) FUSE BLOWING SCHEME

In *fuse blowing* scheme, fuses operate faster than the upstream recloser, and therefore the customers located downstream of the fuses suffer from sustained interruption. To determine whether the fault leads to momentary or sustained interruption in this scheme, $Q_{f,i}$ is mathematically formulated as follows:

$$Q_{f,i}=\sum_{s=s_o}^{s_i} X_{f,s}^{Re}\left(\prod_{s'=s+1}^{s_i}(1-X_{f,s'}^{Fu})\right); \quad \forall f \in F,\ \forall i \in I^a \quad (14)$$

where s_o represents the location of the equipment at the beginning of the feeder (e.g., see X_1 in Figure 1). Also, s' is the index of potential fuse locations between the upstream recloser and faulted section. Therefore, the product term represents the impact of fuses installed between the faulted section and upstream recloser. According to (14), when the closest PD adjacent to the faulted section is a recloser, $\prod_{s'=s+1}^{s_i}(1-X_{f,s'}^{Fu})$ is equal to one, and consequently $Q_{f,i}$ takes a positive value, therefore (13) forces $c_{f,i}$ to be equal to one. This means that the temporary fault leads to momentary interruption. However, if the nearest PD adjacent to the fault is a fuse or if there is no recloser between the faulted section and the beginning of the feeder, $Q_{f,i}$ is equal to zero, which indicates that the fault causes sustained interruption.

2) FUSE SAVING SCHEME

In *fuse saving* scheme, the recloser operates before the downstream fuse blows, so the customers located downstream of the recloser are interrupted momentarily. In other words, fuses operate only for permanent faults in this situation. In this scheme, the formulation of $Q_{f,i}$ in (14) is revised as follows:

$$Q_{f,i}=\sum_{s=s_o}^{s_i} X_{f,s}^{Re}; \quad \forall f \in F,\ \forall i \in I^a \quad (15)$$

According to the above expression, if there is any recloser between the faulted section and the beginning of the feeder, $Q_{f,i}$ takes a positive value, zero otherwise.

By considering the impact of temporary faults on the type of interruptions, the following expression is used to determine the interruption duration of customers when the fault causes a momentary interruption.

$$C_{t,f,i,j,k}^{t} \geq cdf_{t,f,i,j,k}^{M} c_{f,i}; \quad \forall t \in T,\ \forall f \in F,\ \forall i \in I^a, \quad \forall 2j=i,\ \forall k \in K \quad (16)$$

where, $cdf_{t,f,i,j,k}^{M}$ is the momentary interruption cost imposed on customers due to the occurrence of a temporary fault. In (16), when $c_{f,i}$ is equal to one, customers experience a momentary interruption. However, when the temporary fault leads to a sustained interruption, the customer interruption duration is calculated through expressions (17)-(19c) formed by using expressions (10)-(12c) wherein the right-hand-side of (10)-(12c) is multiplied by binary variable $1-c_{f,i}$, and $C_{t,f,i,j,k}^{p}$ is also replaced by $C_{t,f,i,j,k}^{t}$ $(*)$.

$$(10)-(12c) \xrightarrow{*} (17)-(19c)$$

Besides the formulas, there are some technical and economic constraints which restrict the solution space of the problem. These constraints are described in the following subsections.

C. TECHNICAL CONSTRAINTS

The technical constraints represent the coordination between PDs and the candidate locations for both PDs and CDs. In this paper, it is assumed that all equipment operates properly and are fully coordinated. In addition, to avoid deploying two kinds of equipment at the same location, the following constraint is adopted in the model.

$$X_{f,s}^{RCS}+X_{f,s}^{MS}+X_{f,s}^{Fu}+X_{f,s}^{Re} \leq 1; \quad \forall f \in F,\ \forall s \in S \quad (20)$$

In practice, the coordination of PDs is always the important issue in power systems. To consider this issue, the number of allowable reclosers in each feeder is restricted to a predefined number as follows:

$$\sum_{s\in S} X_{f,s}^{Re} \leq \overline{N}_f^{Re} \quad (21)$$

D. ECONOMIC CONSTRAINTS

The budget limits may affect the number of allowable equipment that can be installed in the network. Therefore, the following constraint can be embedded in the model as follows:

$$\sum_{f\in F}\sum_{s\in S}\begin{pmatrix} X_{f,s}^{RCS}CIC_{f,s}^{RCS} \\ +X_{f,s}^{MS}CIC_{f,s}^{MS} \\ +X_{f,s}^{Fu}CIC_{f,s}^{Fu} \\ +X_{f,s}^{Re}CIC_{f,s}^{Re} \end{pmatrix} \leq Budget \quad (22)$$

where (22) restricts the total budget allocated by the DisCo. Needless to mention, the constraint can be translated to a cap over the number of devices that can be installed.

It should be pointed out that constraints (11a)-(12b), (14), and (16) contain the product of binary and integer variables as well as the product of multiple binary variables, and therefore they are non-linear. To linearize the product of binary and integer variables, the method applied in [36] is used. Also, the method applied in [37] is used to linearize the product of multiple binary variables. It is worthwhile to point that the methods convert the non-linearities into linear inequality constraints.

Considering the objective function (1) and the related constraints (2)-(22), the simultaneous placement of PDs and CDs is formulated in MIP format which can be effectively solved via available solvers. The proposed model deems the impact of permanent and temporary faults as well as their consequences based on the coordination of fuses and reclosers. The main input data consists of the equipment costs data, set of candidate locations for equipment installation, network configuration, reliability parameters, as well as technical and

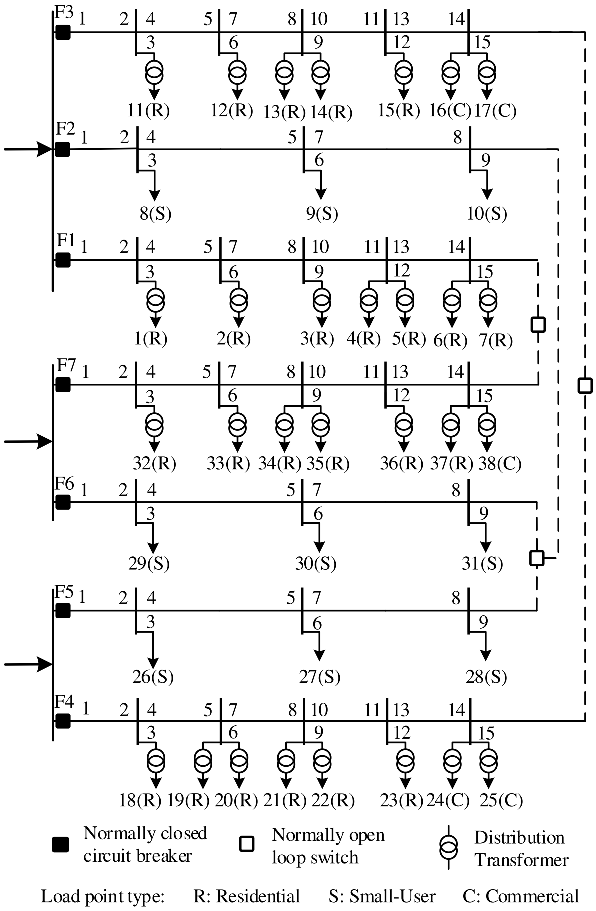

FIGURE 2. Single line diagram of RBTS-Bus4.

economic constraints. The decision variable is the location of devices. The output data is the number and location of PDs and CDs as well as the system costs and reliability indices.

III. CASE STUDY

In this section, the performance of the proposed model is examined through applying it to a standard test system and a real distribution network. A brief description over the standard test system is followed by discussion over the simulation results and sensitivity analyses. Then, the model is applied on a real-life distribution network.

A. RBTS-BUS4

In this subsection, the effectiveness of the proposed model is verified by applying it to the 11 kV network connected to Bus 4 of Roy Billinton test system (RBTS-Bus4). The single line diagram of the system is shown in Figure 2. In the network, 4700 residential customers, 70 commercial customers, and 9 small-user customers are fed through 38 load points from 7 feeders. Each load point is specified with a number following a letter. The number indicates the load point number and the letter designates the load point type (defined in the figure). The network data including permanent failure rate of feeder sections, load level, and the number and type of

TABLE 1. System costs, reliability indices, and runtime in Case I.

Costs (US k$)			Reliability indices				Runtime
Eq.	Int.	Total	MAIFI	SAIFI	SAIDI	AENS	(sec.)
–	4102.75	4102.75	0	1.26	0.77	2.31	0.36

MAIFI(int./cust.yr.): Momentary Average Interruption Frequency Index
SAIFI(int./cust.yr.): System Average Interruption Frequency Index
SAIDI(h./cust.yr.): System Average Interruption Duration Index
AENS(kWh/cust.yr.): Average Energy Not Supplied
int.: interruption, cust.: customer, yr.: year, h.: hour, sec.: second

customers is borrowed from [38]. The customer damage functions (CDFs) for sustained and momentary interruptions are extracted from [39]. The temporary failure rates are assumed to be four times more than the permanent failure rates. The capital investment and installation costs of recloser, fuse, RCS, and MS are considered US $6000, 500, 4700, and 500, respectively. Also, the annual maintenance cost is considered as 2% of the capital investment and installation costs [9], [19]. The simulation is conducted for 15-year study horizon in which annual load growth and discount rates are 3% and 8%, respectively. The time needed for remote switching, manual switching, and repair actions are assumed to be 5, 60, and 180 minutes, respectively [40]. To model the coordination between fuses and reclosers during temporary faults, *fuse blowing* scheme is considered. Also, for considering the reclosing capability of CBs, it is assumed that only recloser can be installed at the beginning of the feeder. Furthermore, it is assumed that fuses are not allowed to be installed in the main feeder and at most two reclosers can be installed in each feeder. It should be noted that every branches in the test system either equipped with a transformer or not is considered as laterals. Also, the impact of normally open switches at the end of the feeders, i.e., tie-points, is considered in the simulations. The proposed formulation is performed in the GAMS software [41] and solved using the CPLEX 11.0 solver [42], where it uses the branch and cut algorithm [42].

Here, three cases are simulated, and the results are put under investigation.

Case I: Here, the original network is considered wherein neither PDs, i.e., reclosers and fuses, nor CDs, i.e., MSs and RCSs, are deployed, while a CB is already placed at the beginning of each feeder. The case is simulated, and the achieved results are provided in Table 1. As can be seen, the total interruption cost is about US k$4103 in which the interruption cost induced by temporary faults is four times more than the cost originated from permanent faults. This is derived from the fact that there is no available PD in the network, and thus any temporary fault results in sustained interruption. In other words, there is no momentary interruption in this situation, therefore, MAIFI is zero. Meanwhile, the runtime for this case is 0.36 seconds.

Case II: In this case, sequential placement of PDs and CDs is considered. To do so, first, PD placement is conducted. Then, CD placement is considered in which the location of PDs is obtained from the PD deployment problem. In other

TABLE 2. Optimal location of equipment in Case II.

Feeder	Location			
	RCS	MS	Fuse	Recloser
1	13	4,8,11	–	1,14
2	4,7	2,8	–	1,5
3	13	5,8,10	–	1,14
4	13	5,7,10	–	1,14
5	4,8	2,7	–	1,5
6	4,8	2,5	–	1,7
7	13	5,8,10	–	1,14

TABLE 3. System costs, reliability indices, and runtime in Case II.

Costs (US k$)			Reliability indices				Runtime
Eq.	Int.	Total	MAIFI	SAIFI	SAIDI	AENS	(sec.)
166.44	283.77	450.21	0.88	0.22	0.29	0.72	1.18

TABLE 4. Optimal location of equipment in Case III.

Feeder	Location			
	RCS	MS	Fuse	Recloser
1	14	5,8,11	–	1
2	5	2,4,8	–	1,7
3	14	2,8,10	3	4
4	14	5,7,10	–	1
5	2,7	5,8	–	3,4
6	2,8	5,7	–	3,4
7	14	4,8,10	–	1

TABLE 5. System costs, reliability indices, and runtime in Case III.

Costs (US k$)			Reliability indices				Runtime
Eq.	Int.	Total	MAIFI	SAIFI	SAIDI	AENS	(sec.)
133.56	270.73	404.29	0.95	0.27	0.30	0.73	1.30

words, in this case, two sub-problems are solved sequentially, where in the first one only the placement of PDs is regarded and CDs are not allowed to be placed; and in the second one the deployment of CDs is considered in the presence of the PDs obtained from the first sub-problem. This case is a comparison benchmark illustrating that the placement of CDs in the presence of PDs may not reach the optimum solution. The obtained results are shown in Tables 2 and 3. According to the results, two reclosers are installed in each feeder to alleviate the impact of temporary and permanent faults. Also, the system interruption and total costs are considerably decreased by about 93% and 89%, respectively, compared to those in Case I. In addition, installing the PDs results in reduction of SAIFI index by about 83%. Also, installing CDs in this case as compared with Case I leads to a significant decrement in SAIDI and AENS indices. It should be noted that, in this case, all temporary faults result in momentary interruptions because of the deployment of a recloser at the beginning of each feeder. That is why MAIFI is not zero in this case compared with that in Case I. The runtime for the first and second sub-problems are 0.65 and 0.53 seconds, respectively. In total, the simulation time in this case is 1.18 seconds which is greater than that in Case I since the number of variables and constraints in Case II grows.

Case III: In this case, simultaneous placement of PDs and CDs is considered. The case illustrates that the optimum solution of equipment deployment is achieved when the placement of both PDs and CDs is modeled in one problem. The obtained results are provided in Tables 4 and 5. As can be seen in Table 3, each feeder is equipped with four CDs. Also, a few PDs are installed at the begining of each feeder except Feeder 2 in which a recloser is employed in the middle of the feeder. According to Table 5, the simultaneous placement results in a much more economic and reliable solution in comparison with the base case where PDs and CDs are not installed in the network. More accurately, system interruption cost and total cost in this case are decreased by about 93% and 90%, respectively, in comparison with the costs in Case I. In addition, the reclosers are mostly installed at the beginning of the feeders to lessen the impact of temporary faults, and the RCSs are employed near the location of load points with higher load levels and CDFs. The simulation in this case is executed in 1.30 seconds.

By comparing Case I with Cases II and III, it can be concluded that installing both PDs and CDs remarkably reduces the system cost and improves the reliability level of the network. This occurs due to the capability of PDs in protection and CDs in prompt service restoration to customers in emergency situations. Comparing the achieved results in Cases II and III, it is revealed that the investment cost of equipment in Case III is about US k$32.88 (reduction from US $166.44 to US $133.56) less than the investment cost in Case II, in the sense of 20% saving. Also, the system interruption cost is reduced from US $283.77 in Case II to US $270.73 in Case III, which is equivalent to 4.6% reduction (i.e., US $13.04). This observation indicates that the simultaneous placement of PDs and CDs results in about 10% increment in the benefit accomplished from the device placement (reduction from US $450.21 to US $404.29 in total system cost). This means that DisCos must make decision about placement of PDs and CDs simultaneously. To better illustrate the effectiveness of the proposed model, the runtime of the cases is also provided in Tables 1, 3, and 5. As can be seen, the runtime in Case III is longer than the runtime in the other cases. This occurs because the number of variables and constraints rises when making decision about both PDs and CDs is the target. However, needless to mention, the runtimes are tolerable since the problem is solved as a planning study.

1) RECLOSER-FUSE COORDINATION MODE

Here, to scrutinize the impact of *fuse saving* scheme, Case III is simulated again, and the results are shown in Tables 6 and 7. As can be seen, by using *fuse saving* scheme, the number of fuses is increased as compared with the number of fuses achieved when *fuse blowing* scheme is used. This occurs since installing fuses at the beginning of laterals restricts consequences of the downstream faults. Therefore, in *fuse saving* scheme, both momentary and sustained interruption costs

TABLE 6. Impact of fuse saving on location of equipment in Case III.

Feeder	Location			
	RCS	MS	Fuse	Recloser
1	14	5,10	3,6,9,12	1
2	5	2,4,7,8	3,6,9	1
3	14	5,10	2,6,9,12	1
4	14	5,10	3,6,9,12	1
5	5	2,4,7,8	3,6,9	1
6	5	2,4,7,8	3,6,9	1
7	14	5,10	3,6,9,12	1

TABLE 7. Impact of fuse saving scheme on system costs, reliability indices, and runtime in Case III.

Costs (US k$)			Reliability indices				Runtime
Eq.	Int.	Total	MAIFI	SAIFI	SAIDI	AENS	(sec.)
115.79	246.58	362.38	1.03	0.18	0.26	0.66	0.93

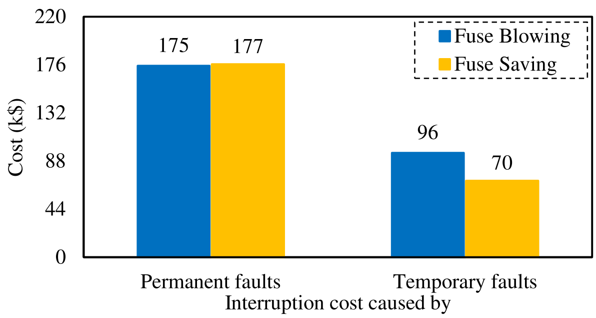

FIGURE 3. Impact of fuse saving scheme on interruption costs caused by permanent and temporary faults in Case III.

are reduced. Also, the investment cost is slightly decreased as compared to that of *fuse blowing* scheme, and more importantly less system cost (reduction from US k$404.29 to US k$362.38) is imposed on the DisCo.

To be more accurate, the interruption costs caused by permanent and temporary faults for *fuse blowing* and *fuse saving* schemes are depicted in Figure 3. As can be seen, although the interruption cost resulted from permanent faults is slightly increased, the interruption cost originated from temporary faults is reduced by 27.1% when the *fuse saving* scheme is applied. This reveals the huge impact of *fuse saving* scheme in comparison to *fuse blowing* scheme on reduction of interruption cost caused by temporary faults. Along with the less imposed cost, the results in Table 7 verify that *fuse saving* mode can greatly improve service reliability. Hence, applying *fuse saving* scheme leads to a more cost-effective and reliable strategy.

As another observation, comparing the reliability indices in the *fuse blowing* and *fuse saving* schemes (see Tables 5 and 7), it is clear that MAIFI increases from 0.95 to 1.03 in exchange for a decrease in SAIFI from 0.27 to 0.18 when *fuse saving* scheme is used. This is because the operation of the upstream recloser of the *fuse saving* fuse affects much more customers than if only the fuse operates. For a fault downstream of the *fuse saving* fuse, either permanent or temporary, the recloser

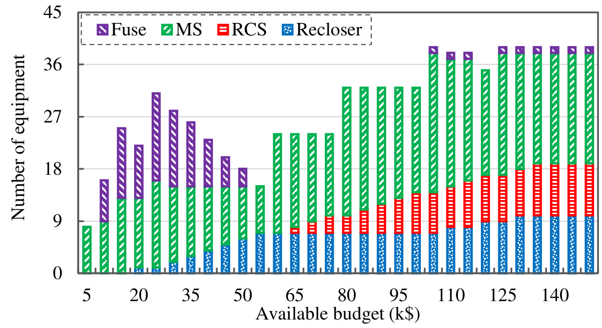

FIGURE 4. Number of equipment for different budget limits in Case III.

recloses, therefore, many customers experience a momentary interruption. This is in contrast with a *fuse blowing* scheme, wherein despite the interruptions guaranteed to be always sustained, it is localized downstream of the fuse. This means that other customers downstream of the recloser do not experience a momentary interruption. As a result of the above trade-off, MAIFI is increased and SAIFI is decreased when *fuse saving* scheme is applied. The obtained results are consistent with the discussion on *fuse saving* fuses in [21].

2) BUDGET LIMITATION

DisCos are usually confronted with limited budget to equip their networks, so it makes sense to install equipment based on the allocated budget. With this in mind, the budget in (22) is increased from US k$5 to US k$150, and Case III is simulated again. The achieved results are shown in Figure 4. As can be seen, tightening the budget constraint leads to install more MSs and fuses because of their low prices in comparison with the price of the other equipment. Though, when there is no restriction on the budget allocated to DisCos, installing RCS, due to its advantages in prompt service restoration, and reclosers, owing to their protective characteristic, is more preferable. As another observation, when the budget is increased, reclosers are installed firstly, and RCSs are then employed. The number of MSs and fuses depends on the number of reclosers and RCSs such that when the number of either reclosers or RCSs rises, the number of MSs or fuses is decreased. This occurs because reclosers also have the manual capability of MSs and the protective characteristic of fuses. Also, RCSs are able to isolate and restore the interrupted load points from the faulted zone much faster than MSs. So, when a recloser or an RCS is installed, there is no need for further MSs or fuses.

B. FINNISH DISTRIBUTION NETWORK

In this subsection, to examine the performance of the proposed model on larger distribution networks, a Finnish 20 kV urban distribution network is considered as shown in Figure 5. In the network, 144 load points are fed through 6 feeders originated from the main substation. The network data involving network configuration and customers information are taken from [43]. Other information and assumptions are

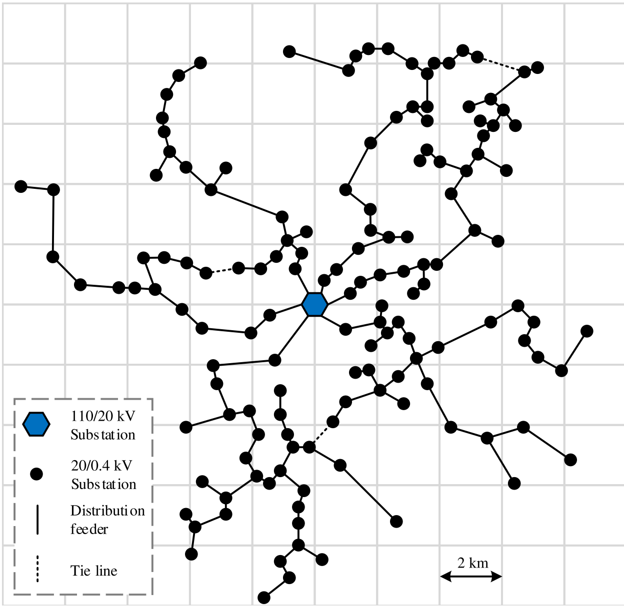

FIGURE 5. Single line diagram of Finnish distribution network.

TABLE 8. Optimal number of equipment in different cases for finnish distribution network.

Case	Number			
	RCS	MS	Fuse	Recloser
I	–	–	–	–
II	14	36	5	12
III	12	40	1	10

TABLE 9. System costs, reliability indices, and runtime in different cases for finnish distribution network.

Case	Costs (US k$)			Reliability indices				Runtime
	Eq.	Int.	Total	MAIFI	SAIFI	SAIDI	AENS	(sec.)
I	–	6450.12	6450.12	0	0.79	0.48	49.71	2.34
II	188.34	457.13	645.47	0.44	0.13	0.08	12.65	13.42
III	162.88	462.17	625.05	0.44	0.13	0.08	12.75	149.72

the same as those considered for RBTS-Bus4. The three cases are simulated, and the obtained results are provided in Tables 8 and 9.

The results in Table 8 reveal that simultaneous placement can thoroughly change the number of equipment when they are installed sequentially. Also, in Case III, only one fuse is installed in the network. This occurs because of the manual capability and cost-effectiveness of MS in comparison with fuse when decision making about the placement of the devices is done simultaneously. As can be see in Table 9, the simultaneous placement leads to 13.5% and 3.2% savings in investment cost (reduction from US k$188.34 to US k$162.88) and total cost (reduction from US k$645.48 to US k$625.04), respectively, as compared with the sequential placement. Hence, the simultaneous placement of the devices leads to a cost-effective solution with suitable reliability level. It is worthwhile to mention that considering both PDs and CDs in simultaneous placement problem increases the computational time. This is because of the large number of variables and inequalities which grows the complexity of the placement problem.

IV. CONCLUSION

The paper proposed a mathematical model for decision making about the optimal deployment of reclosers, fuses, RCSs, and MSs in one placement problem. The model was developed in MIP fashion which can reach the global optimal solution. The aim of the model is to minimize equipment and system interruption costs. The model considers both sustained and momentary interruptions as well as the coordination between fuses and reclosers when a temporary fault occurs. To examine the performance of the proposed model, it was applied to a test system and a real-life distribution network. The results revealed that simultaneous placement of the devices leads to a more economical solution with proper service reliability. In addition, using *fuse saving* scheme in comparison with *fuse blowing* scheme may reduce the system cost and improve service reliability. Also, the MAIFI is increased while SAIFI is decreased if *fuse saving* scheme is applied. In addition, it was illustrated that in case of budget limits, installing MSs and fuses results in a better solution, while when there is no restriction on the budget, installing RCSs and reclosers brings a better solution. Also, applying the proposed model on a real distribution system revealed the effectiveness and capability of the method on larger systems.

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MILAD IZADI (S'16) received the B.Sc. degree in electrical engineering from Razi University, Kermanshah, Iran, in 2015, and the M.Sc. degree in electrical engineering from the Sharif University of Technology, Tehran, Iran, in 2017. He is currently pursuing the Ph.D. degree with the University of California, Riverside, CA, USA. His research interests include power system planning, operation, reliability, and optimization.

AMIR SAFDARIAN (S'11–M'15) received the B.Sc. degree from Tehran University, Tehran, Iran, in 2008, and the M.Sc. and Ph.D. degrees from the Sharif University of Technology, Tehran, in 2010 and 2014, respectively, all in electrical engineering, where he is currently an Assistant Professor. His research interests include distribution system operation and planning, smart grid issues, and power system reliability and resilience. He was a recipient of the 2013 IEEE Power System Operation Transactions Prize Paper Award, the 2016 IEEE Iran Section Best Ph.D. Dissertation Award, and the 2019 IEEE Iran Section Young Investigator Award and on the list of outstanding reviewers of the IEEE Transactions on Sustainable Energy, in 2016.

MOEIN MOEINI-AGHTAIE (M'15) received the M.Sc. and Ph.D. degrees in electrical engineering from the Sharif University of Technology, Tehran, Iran, in 2010 and 2014, respectively, where he is currently an Assistant Professor with the Department of Energy Engineering. His current research interests include reliability and resilience studies of modern distribution systems, especially in the multi-carrier energy environment, and charging management of plug-in hybrid electric vehicles.

MATTI LEHTONEN received the M.S. and Licentiate degrees from Aalto University (formerly Helsinki University of Technology), Espoo, Finland, in 1984 and 1989, respectively, and the D.Sc. degree from the Tampere University of Technology, Tampere, Finland, in 1992, all in electrical engineering. Since 1987, he has been with VTT Energy, Espoo, and since 1999, he has been with the Department of Electrical Engineering and Automation, Aalto University, where he is currently a Professor of IT applications in power systems. His research interests include earth fault problems and harmonic-related issues, and applications of information technology in distribution automation and distribution energy management.