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Electricity Distribution System Switch Optimization Under Incentive Reliability Scheme

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ABSTRACT The judicious placement of disconnecting switches is an efficient means to enhance the reliability of distribution networks. Aiming at optimizing the investment in these switches, this paper presents a mathematical programming-based model considering the installation of remote-controlled and manual switches at various locations in the distribution network. The proposed model not only yields the optimal location and type of switches in the main feeders but also specifies the optimal type of tie switches, i.e., backup switches at the reserve connection points. Incentive reliability regulation in the form of a reward-penalty scheme is incorporated into the proposed model to take the distribution service reliability worth into account realistically. In addition to this cost, the revenue lost due to energy undelivered during the distribution network faults is considered to determine the unreliability costs more accurately. In order to estimate such reliability-related costs, a novel reliability assessment technique is developed and integrated into the proposed switch optimization model. Formulated as an instance of mixed-integer linear programming, the proposed model is applied to a test distribution network, and the outcomes are investigated in detail.

INDEX TERMS Electricity distribution system, mixed-integer linear programming, reliability, reward-penalty scheme, switch optimization.

NOMENCLATURE

INDICES

i	Index for zones of the reward-penalty scheme.
$l, \bar{l}$	Indices for feeder sections.
r	Index for reserve connection points.
n	Index for load nodes.

SETS

L	Set of all feeder sections.
R	Set of reserve connection points.
R_n	Subset of R containing the tie switch corresponding to node n.
$\Gamma_{l,n}$	Subset of L, which is comprised of the feeder sections between feeder section l and node n.
Ω	Set of all load nodes.
Ω_l^{Dn}	Subset of Ω, which includes the nodes downstream of feeder section l.
Ω_l^{Up}	Subset of Ω containing the nodes upstream of feeder section l.

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PARAMETERS

IC^{RC}, IC^{M}	Investment costs for an RCS and an MS, respectively.
IPR	Incentive penalty rate.
IRR	Incentive reward rate.
M	A sufficiently large number.
N_n	Total number of customers connected to load node n.
OMC^{RC}, OMC^{M}	Operation and maintenance costs for an RCS and an MS, respectively.

P_n	Average demand at node n.
$PCap$	Penalty cap.
$RCap$	Reward cap.
RT	Repair time for a faulty feeder section.
ST^{RC}, ST^{M}	Switching times for RCSs and MSs, respectively.
T	Useful lifetime of the distribution switches.
α	Annual interest rate.
δ^T	Annuity factor for the investment cost.
λ_l	Failure rate of feeder section l.
ρ	Expected revenue from delivering one unit of electrical energy to the customers.

VARIABLES

$EENS$	Expected energy not supplied.
Inv	Investment cost of distribution switches.
OF	Objective function.
Op	Operational cost of distribution switches.
PRS	Cost imposed by the reward-penalty scheme.
RRC	Reliability-related costs.
$SAIDI$	System average interruption duration index.
x_r^{RC}	Binary investment variable, which becomes 1 if an RCS is installed at reserve connection point r, being 0 otherwise.
$x_l^{R,M}$	Binary investment variable, which is equal to 1 if an MS is installed at the receiving end of feeder section l, being 0 otherwise.
$x_l^{R,RC}$	Binary investment variable, which is equal to 1 if an RCS is installed at the receiving end of feeder section l, being 0 otherwise.
$x_l^{S,M}$	Binary investment variable, which is equal to 1 if an MS is installed at the sending end of feeder section l, being 0 otherwise.
$x_l^{S,RC}$	Binary investment variable, which is equal to 1 if an RCS is installed at the sending end of feeder section l, being 0 otherwise.
β^{DZ}, β^{PC}	Binary variables indicating whether their corresponding auxiliary variables can have a non-zero value.
σ_i	Non-negative auxiliary variable related to zone i of the reward-penalty scheme.
$\tau_{l,n}$	The expected annual interruption duration for the customers at node n due to faults on feeder section l.

I. INTRODUCTION

Reliability plays such an essential role in the planning and operation of distribution networks that it can account for almost 50% of the total network cost [1]. Among several strategies available for enhancing the continuity of supply or service reliability, the installation of disconnecting switches is one of the most effective and common alternatives. Thus, an optimal investment in distribution switches not only can significantly improve the network reliability but also increases the cost-efficiency of the system. Accordingly, in recent years, a wide range of research studies have been carried out in the field of reliability-oriented distribution switch optimization. Based on their modeling techniques and problem-solving approaches, these research works can generally be categorized into two groups: heuristic and mathematical programming-based.

Adopting the heuristic modeling approach, a three-state version of particle swarm optimization (PSO) was presented in [2] to simultaneously find the optimal number as well as locations of sectionalizers and circuit breakers in a distribution network. Reference [3] proposed a multi-objective optimization model for distribution switch placement problem based on a PSO algorithm with the goal of minimizing the number of installed switches as well as the number of customer interruptions. Using a differential search algorithm, authors in [4] developed a multi-objective formulation for optimal placement of remote-controlled switches (RCSs) so as to minimize the cost of expected energy not supplied (EENS) together with the cost of installed switches. Aiming at minimizing the investment, operational, and interruption costs considering uncertainties, authors in [5] proposed a mixed-integer nonlinear programming (MINLP) optimization model for placement of switches and reclosers, which was solved by a differential evolution technique.

Nonetheless, the heuristic or meta-heuristic methods leveraged in such studies neither can guarantee the attainment of an optimal solution nor can provide a measure of the distance from the global optimum. To deal with such an important deficiency, more recently, several models have been proposed for the switch optimization problem in a mixed-integer linear programming (MILP) form [6]–[16]. Authors in [6] presented an MILP model for the RCS placement in distribution networks, taking into account customer outage costs as well as the investment and operational costs of the switches. Reference [7] provided a model to determine the number and location of RCSs such that the sum of unreliability cost and cost of the switches was minimized. Reference [8] proposed an MINLP model, which was then linearized to form an MILP problem, in order to determine the number and location of switches, while minimizing the EENS, total energy loss, and investment cost of the switches. Also, authors in [9] developed an MILP model for multi-stage switch planning with the goal of minimizing the total interruption cost as well as investment and operational costs of the switches. Similarly, an MILP switch optimization model was proposed in [10], which determined the placement of RCSs not only in the main feeders but also in the laterals. In [11], an MILP model was represented for the manual switch (MS) and RCS placement, which integrates switch malfunction probability into the problem. Formulated as an instance of MILP, [12] developed a model to find the optimal locations of fault indicators, MSs, and RCSs. Authors in [13] derived an MILP formulation for the optimal RCS deployment problem such that the expected profit was maximized while the financial risk, which was imposed by uncertainties, was minimized. In [14], switch failures were taken into account in the MILP switch optimization problem, and their impact on switch allocation was studied. Reference [15] extended the previous MILP switch optimization models so as to conduct simultaneous placement of fuses, reclosers, MSs, and RCSs. Finally, authors in [16] developed an MILP model for concurrent integration of fault indicators, MSs, and RCSs into a distribution network with branch lines.

Each of these studies made a notable contribution toward improving the switch placement models in terms of efficiency and applicability. However, to the best of our knowledge, all these studies share an unpragmatic assumption regarding the tie switches installed in the reserve connection points, which connect neighboring feeders to each other for the sake of speeding up service restoration in case of faults. Accordingly, in [2]–[10], it was assumed that not only a specific type of tie switch had existed prior to determining the location of other switches, but also only one switch option was considered for installation in the candidate locations of the distribution networks, which neither was practical nor would bring about the optimal solution for the simultaneous placement of MSs and RCSs. References [11]–[15] extended their models and considered both MSs and RCSs as available alternatives for integration into distribution networks. Nevertheless, these studies assumed that tie switches, which were installed prior to solving the switch optimization problem, had a definite switching time lower than the rest of installed switches. Also, they did not consider the fact that distribution companies (DISCOs) might intend to decide whether installing an RCS or MS in each of the reserve connection points is economical. First of all, there is no guarantee that without making any investments in them, the existing switches in the reserve connection points (tie switches) operate faster than other switches in the network. Secondly, owing to the high investment cost of RCS, the assumption that installing this kind of switch in those locations is the optimal solution for every distribution network might not be practical. Hence, in addition to finding the optimal placement of MSs and RCSs in the main feeders, determining which switch type must be installed in the backup connection points should also be taken into consideration.

Furthermore, based on the classical approach developed in [17], the authors in [6], [7], [9]–[15] quantified the unreliability by leveraging a widely used index, the total customer interruption cost. This measure, which is a function of the network topology, interruption duration, equipment failure rate, and customer damage function, can appropriately reflect the network performance from the reliability perspective. However, in practical applications, the interruption cost for customers cannot be precisely determined since it highly depends on a group of parameters including the customer damage functions of various load nodes, whose values are difficult to assess. More importantly, this classical measure does not reflect the unreliability costs that the DISCOs are forced to incur.

In practice, the unreliability costs imposed on the DICOSs consist of the regulatory penalties incurred (or rewards lost) based on the incentive reliability schemes as well as the revenue lost due to the undelivered energy to the customers during power cuts [18], [19]. Incentive reliability regulations are typically applied to average system reliability indices such as system average interruption duration index (SAIDI) [19], [20]. Moreover, the amount of revenue lost due to the undelivered energy is calculated based on the EENS. Thus, in order to have a precise estimation of the unreliability costs, a sufficiently accurate distribution reliability assessment model to quantify SAIDI and EENS must be devised and incorporated into the optimization model. To the best of our knowledge, such a reliability assessment model is missing in the state-of-the-art literature on distribution switch optimization. Among the investigated works, in [16], authors developed an approximate technique to model SAIDI based on the EENS value. The authors then set an upper bound for SAIDI and considered the cost imposed by EENS to ensure the reliable operation of the distribution network. However, the approach used to determine SAIDI is oversimplified and fails to account for the number of customers affected by each contingency. Therefore, the SAIDI value estimated based on EENS may have a significant error in practical applications. Moreover, the model developed in [16] for EENS is based on the assumption that type of tie switches is known a priori.

Given the points mentioned earlier, this paper proposes an MILP model for the reliability-oriented switch placement problem, while considering both MS and RCS as alternatives for installation in the sending and receiving ends of feeder sections and determining the optimal switch type in the backup connection points. The objective function of the proposed model consists of investment, installation, operational, and maintenance costs of MSs and RCSs together with a reliability-related cost including regulatory rewards and penalties, and revenue lost due to power interruptions. In order to model the reliability-related cost, which is a function of EENS and SAIDI, a precise reliability assessment model is proposed, which is consistent with the standard definitions stated in [21]. In summary, the major contributions of this paper are represented in what follows:

- Devising a novel switch optimization model, which determines not only the location and type of switches in the main feeders but also the type of every tie switch.
- Incorporating incentive reliability regulation in the form of a reward-penalty scheme into the switch optimization model to practically account for the reliability-related costs imposed by the regulatory authorities.
- Developing an MILP reliability assessment model to attain EENS and SAIDI.
- Proposing an innovative MILP model for the non-linear reward-penalty function.

The remainder of this paper is organized as follows. The switch optimization problem is stated in Section II. The problem is modeled and formulated in Section III as an instance of

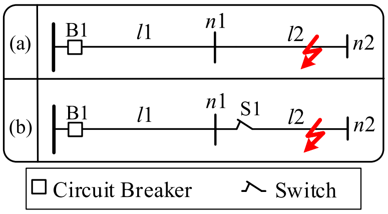

FIGURE 1. A simple distribution feeder.

MILP, which is then implemented on a test distribution network in Section IV. Finally, Section V concludes the paper.

II. STATEMENT OF THE PROBLEM

The most important role of disconnecting switches, which is referred to as switches throughout this paper for the sake of simplicity, is fault isolation during post-fault reconfiguration to minimize the impact of a failure on the grid customers. As an illustrative example, consider the simple distribution feeder depicted in Fig. 1. In configuration (a), a fault on feeder section $l2$ results in the tripping of circuit breaker B1. Thus, customers connected to load points $n1$ and $n2$ remain disconnected until the faulty feeder section $l2$ is repaired. Nonetheless, for the topology illustrated in Fig. 1 (b), after the feeder is de-energized via B1, switch S1 is opened to isolate $l2$ and then B1 is closed to reconnect the power supply for load point $n1$. Therefore, in case a fault occurs on $l2$, load node $n1$ can be restored after a so-called *switching time*, which is far lower than the repair time. Hence, by adding a switch, i.e., S1, the network reliability is enhanced, since the average interruption time of the network customers decreases.

The disconnectors can be either MS or RCS. In order to operate an MS, the repair crew must visit it, which can dramatically increase the switching time. Thus, due to their lower switching time, RCSs improve reliability more than MSs, yet they are more expensive.

Another practical point to be considered is that although electricity distribution networks are operated radially, they often have a meshed design, i.e., there is a normally-open tie switch or backup connection at the end of each feeder. This normally-open switch is used in the post-fault network reconfiguration to restore part or all of the demand at the end of the corresponding feeder. In the existing literature, it is typically assumed that all backup connections are equipped with RCSs. Nonetheless, in the model proposed in this paper, the type of the normally-open switches is also determined via the optimization process.

Although the installation of switches in the network enhances the continuity of supply or service reliability, it requires initial investments and also increases the operational costs of the grid. Hence, in order to reach an optimal switch configuration, the network reliability must be compromised for the corresponding investment and operational costs. In other words, a cost-worth analysis has to be carried out to determine the optimal number, place, as well as type (i.e., manual and remote-controlled) of the switches within the network.

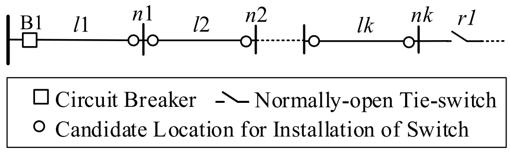

FIGURE 2. A typical distribution feeder.

In this paper, the reliability worth is estimated based on an incentive reliability regulation implemented on SAIDI as well as the revenue lost due to undelivered energy to the customers during power outages. Such incentive reliability regulations, known as reward-penalty schemes, provide financial motivations for DISCOs to keep their service reliability at an acceptable level [18]–[20], [22]. Compared to the state-of-the-art literature on distribution switch optimization in which customer interruption cost approach is employed, reward-penalty values provide a more realistic measure of the reliability worth. This is because, in practice, DISCOs are subject to incentive reliability schemes, not the interruption cost estimated from a customer damage function.

Thus, this paper aims to propose an optimization model to determine the number, place, and type of switches in the presence of reward-penalty schemes.

III. PROBLEM MODELING AND FORMULATION

In this section, the modeling approach is presented first. Then, a standard mathematical programming model is developed for reliability-constrained switch optimization in distribution networks.

A. PROBLEM MODELING

In the proposed model, we consider the typical distribution feeder with a normally-open tie switch or reserve connection as depicted in Fig. 2. As per this figure, both ends of each feeder section are considered candidate locations for installation of switches. For each candidate location, we consider two binary variables, one for the decision on the installation of an RCS and another corresponding to an MS. Thus, for each feeder section l, four binary variables are considered, namely $x_l^{S,RC}$, $x_l^{R,RC}$, $x_l^{S,M}$, and $x_l^{R,M}$. Superscripts S and R stand for sending end and receiving end of feeder section l, while RC and M denote type of switches, i.e., remote-controlled and manual, respectively. It is worth mentioning that for the first feeder section of each feeder, i.e., the one connected to a substation bus, only the receiving end is considered a candidate location. This is because the sending end of such feeder sections, e.g., $l1$ in Fig. 2, are assumed to be equipped with circuit breakers. Thus, for the sample distribution feeder depicted in Fig. 2, we only have two binary variables $x_{l1}^{R,RC}$ and $x_{l1}^{R,M}$. If a binary variable becomes 1, it means that the corresponding investment should be carried out. For instance, if in the optimal solution, decision variable $x_l^{S,RC}$ is equal to 1, it implies that an RCS must be installed at the sending end of feeder section l.

For each backup connection r, only one binary decision variable is considered in the model, i.e., x_r^{RC}. This is because there has to be at least an MS at each of these locations. Thus, in case x_r^{RC} is equal to 1, an RCS must be installed at the tie switch location r; otherwise, an MS would be installed at that location.

B. OBJECTIVE FUNCTION

Formulated in (1), the objective function is comprised of three terms, namely investment cost Inv, operational cost Op, and reliability-related cost RRC. As can be inferred from (1), the objective is to minimize the annualized system cost. The annuity factor for the investment cost, i.e., δ^T, is defined in (2), as a function of annual interest rate α and useful lifetime of the switches.

$$\text{Minimize } OF = \delta^T Inv + Op + RRC \tag{1}$$

$$\delta^T = \frac{\alpha}{1-(1+\alpha)^{-T}} \tag{2}$$

$$Inv = \left(\sum_{l\in L}\left(x_l^{S,RC}+x_l^{R,RC}\right)+\sum_{r\in R}x_r^{RC}\right)IC^{RC} + \left(\sum_{l\in L}\left(x_l^{S,M}+x_l^{R,M}\right)+\sum_{r\in R}\left(1-x_r^{RC}\right)\right)IC^{M} \tag{3}$$

$$Op = \left(\sum_{l\in L}\left(x_l^{S,RC}+x_l^{R,RC}\right)+\sum_{r\in R}x_r^{RC}\right)OMC^{RC} + \left(\sum_{l\in L}\left(x_l^{S,M}+x_l^{R,M}\right)+\sum_{r\in R}\left(1-x_r^{RC}\right)\right)OMC^{M} \tag{4}$$

$$x_l^{S,RC},\ x_l^{R,RC},\ x_l^{S,M},\ x_l^{R,M},\ x_r^{RC} \in \{0,\ 1\} \tag{5}$$

$$RRC = \rho.EENS + PRS \tag{6}$$

In (3), the investment cost required for installation of RCSs and MSs is represented. It is worth mentioning that without loss of generality, the installation cost of switches in all candidate locations are considered identical in (3) for the sake of simplicity. Nonetheless, non-identical installation costs can readily be taken into consideration. The projected operational cost consists of operation and maintenance cost of all installed switches as expressed by (4). Structurally identical to (3), the operation and maintenance cost of all switches of the same type are considered similar in (4). Expression (5) represents the binary nature of the investment decision variables. According to (6), RRC includes the expected revenue lost due to the undelivered energy, i.e., the first term in the right hand-side of (6), and the cost imposed by the reward-penalty scheme that is formulated in Section III-D. It is worth noting that the reward-penalty scheme is applied to SAIDI. Thus, to calculate the RRC, both EENS and SAIDI are required, which are attained from the reliability assessment model presented in the following section.

C. RELIABILITY ASSESSMENT MODEL

In this section, the mentioned reliability indices are determined by leveraging a novel reliability assessment model. EENS and SAIDI are calculated using (7) and (8), respectively.

$$EENS = \sum_{l\in L}\sum_{n\in\Omega}\tau_{l,n}P_n \tag{7}$$

$$SAIDI = \frac{\sum_{l\in L}\sum_{n\in\Omega}\tau_{l,n}N_n}{\sum_{n\in\Omega}N_n} \tag{8}$$

Expressions (9)–(15) jointly specify $\tau_{l,n}$, i.e., the annual interruption duration for the customers connected to node n due to faults on feeder section l. It is worth mentioning that since the optimization problem minimizes an objective function which is monotonically increasing with respect to the reliability indices, and, thus, the annual interruption duration, $\tau_{l,n}$, this variable is set to its lower bound by the optimization solver.

$$\tau_{l,n} \geq 0; \quad \forall l \in L, \forall n \in \Omega \tag{9}$$

$$\tau_{l,n} \geq \lambda_l ST^{RC}; \quad \forall l \in L,\ \forall n \in \Omega_l^{Up} \cup \Omega_l^{Dp} \tag{10}$$

$$\tau_{l,n} \geq \lambda_l ST^{M}\left(1-x_l^{S,RC}-\sum_{\bar{l}\in\Gamma_{l,n}}\left(x_{\bar{l}}^{S,RC}+x_{\bar{l}}^{R,RC}\right)\right); \quad \forall l \in L, \quad \forall n \in \Omega_l^{Up} \tag{11}$$

$$\tau_{l,n} \geq \lambda_l RT\left(1-x_l^{S,RC}-\sum_{\bar{l}\in\Gamma_{l,n}}\left(x_{\bar{l}}^{S,RC}+x_{\bar{l}}^{R,RC}\right) - x_l^{S,M}-\sum_{\bar{l}\in\Gamma_{l,n}}\left(x_{\bar{l}}^{S,M}+x_{\bar{l}}^{R,M}\right)\right); \quad \forall l \in L, \forall n \in \Omega_l^{Up} \tag{12}$$

Accordingly, expression (9) represents the non-negativity of $\tau_{l,n}$, and (10) implies that the lower bound for annual interruption duration of node n due to the failures in feeder section l equals the failure rate of feeder section l multiplied by the minimum restoration time, which is the switching time of an RCS. This is the case when node n is upstream of feeder section l and there is at least an RCS in between, or when node n is downstream of branch l and there is not only at least one RCS in between, but also the reserve connection at the end of the corresponding feeder is equipped with an RCS. Otherwise, the lower bound for $\tau_{l,n}$ must be modified by other constraints.

For the nodes upstream of feeder section l this is done by expressions (11) and (12). When no RCS, but at least one MS, exists between the faulty feeder section l and an upstream node n, (11) specifies the lower bound for $\tau_{l,n}$. This is because on this occasion, all investment variables $x_{(.)}^{(.),RC}$ in the right hand-side of (11) are equal to 0, whereas at least an investment variable $x_{(.)}^{(.),M}$ in the right hand-side of (12) is equal to 1. Thus, expression (11) governs the lower bound of $\tau_{l,n}$, i.e., $\lambda_l ST^M$, since the right hand-side of (12) is less than or equal to 0 and also the lower bound set by (10) is smaller than $\lambda_l ST^M$. On the other hand, when no switch exists between faulted feeder section l and its upstream node n, (12) dictates the lower bound for $\tau_{l,n}$. Indeed, in such cases, the lower bounds set by (10)–(12) are respectively $\lambda_l ST^{RC}$, $\lambda_l ST^M$, and $\lambda_l RT$. Since the repair time RT is higher than the switching times for MSs and RCSs, constraint (12) becomes active and enforces the lower bound. As an illustration of this situation, in the feeder depicted in Fig. 2, assume that there is a fault on feeder section $l2$, but there is no switch between this section and load node $n1$. As a result, the minimum interruption time of this node would be equal to the repair time of the faulted section since the upstream node cannot be isolated from the section.

Structurally identical to expressions (11) and (12), we have (13) and (14) for the nodes downstream of faulted feeder section l. Nonetheless, for these downstream nodes, equation (15) is also required, which implies that $\tau_{l,n}$ cannot be lower than $\lambda_l ST^M$ if the tie switch of the corresponding feeder is an MS. Accordingly, the interruption duration for node n due to a fault on its upstream feeder section l equals the switching time of an RCS only when both the reserve connection point is equipped with an RCS and at least one RCS is installed between node n and branch l.

$$\tau_{l,n} \geq \lambda_l ST^M \left(1 - x_l^{R,RC} - \sum_{\bar{l}\in\Gamma_{l,n}} \left(x_{\bar{l}}^{S,RC} + x_{\bar{l}}^{R,RC}\right)\right); \quad \forall l \in L, \quad \forall n \in \Omega_l^{Dn} \tag{13}$$

$$\tau_{l,n} \geq \lambda_l RT\left(1 - x_l^{R,RC} - \sum_{\bar{l}\in\Gamma_{l,n}} \left(x_{\bar{l}}^{S,RC} + x_{\bar{l}}^{R,RC}\right) - x_l^{R,M} - \sum_{\bar{l}\in\Gamma_{l,n}} \left(x_{\bar{l}}^{S,M} + x_{\bar{l}}^{R,M}\right)\right); \quad \forall l \in L, \quad \forall n \in \Omega_l^{Dn} \tag{14}$$

$$\tau_{l,n} \geq \lambda_l ST^M \left(1 - \sum_{r\in R_n} x_r^{RC}\right); \quad \forall l \in L,\ \forall n \in \Omega_l^{Dn} \tag{15}$$

D. REWARD-PENALTY SCHEME MODELING

In this section, an MILP model is developed for the reward-penalty scheme, i.e., a regulatory tool based upon which the distribution network regulator rewards the DISCO if it maintains an appropriate reliability level and penalizes it in case it fails to fulfill an adequate level of reliability. Such incentive schemes have been implemented in many countries around the world [22]–[24].

The general structure of the reward-penalty scheme is depicted in Fig. 3. This graph shows the relation between the amount of reward or penalty and a reliability index, e.g., SAIDI. As per this figure, the lower the amount of SAIDI is, the more the reward (the less the penalty) will be. Nonetheless, to limit the financial risks associated with the scheme, reward and penalty values are capped at specific levels [23]. In the zone where SAIDI is less than the reward cap point (RCP), the DISCO will receive a definite reward, i.e., reward cap (RCap). Similarly, in the other zone where SAIDI is more than a penalty cap point (PCP), the DISCO will incur a specific amount of penalty, i.e., penalty cap (PCap). The distance between the PCP and RCP are also divided into three zones by two points, reward point (RP) and penalty point (PP). The slopes of the lines between PCP and PP, and RCP and RP are equal to the incentive penalty rate and incentive reward rate, respectively. Also, as can be inferred from Fig. 3, for the zone with SAIDI between RP and PP, which is known as the dead zone [18], neither penalty nor reward is applied. On these bases, (16)–(27) jointly determine the cost imposed by the reward-penalty scheme, i.e., PRS in expression (6).

$$SAIDI = \sum_{i=1}^{5} \sigma_i \tag{16}$$

$$PRS \geq -RCap + \sigma_2 IRR + \sigma_4 IPR \tag{17}$$

$$\sigma_1 \leq RCP \tag{18}$$

$$\sigma_2 \leq RP - RCP \tag{19}$$

$$\sigma_3 \leq \beta^{DZ}\ \text{(PP-RP)} \tag{20}$$

$$\sigma_4 \leq PCP - PP \tag{21}$$

$$\sigma_5 \leq \beta^{PC} M \tag{22}$$

$$\beta^{DZ} \leq 1 + \frac{\sigma_2 - (RP - RCP)}{RP - RCP} \tag{23}$$

$$\beta^{PC} \leq 1 + \frac{\sigma_4 - (PCP - PP)}{PCP - PP} \tag{24}$$

$$\beta^{DZ} \geq \beta^{PC} \tag{25}$$

$$\sigma_i \geq 0; \quad \forall i \in \{1, \ldots, 5\} \tag{26}$$

$$\beta^{DZ},\ \beta^{PC} \in \{0, 1\} \tag{27}$$

In order to model the reward-penalty scheme, five non-negative variables, σ_i, are leveraged, each of which corresponds to one of the zones in the reward-penalty scheme as illustrated in Fig. 3. The aggregate of these variables is equal to SAIDI, which is represented in (16). Also, the total cost imposed by the reward-penalty scheme is determined in (17). It is worth noting that since the objective function is strictly increasing with respect to the reward-penalty cost, PRS will always be set to its lower bound by the optimization solver. Constraints (18)–(22) specify the upper bounds for variables σ_i. As a logical constraint, equation (23) ensures that the variable associated with the dead zone, i.e., σ_3, can take a non-zero value only when σ_2 reaches its maximum value. In the same manner, expression (24) guarantees that σ_5 would have a non-zero value only after σ_4 reaches its upper bound. As an extra logical constraint, (25) is added to the model to enhance the efficiency of the optimization solver. Finally, expressions (26) and (27) imply the non-negativity of variables σ_i, and the binary nature of variables β^{DZ} and β^{PC}, respectively.

IV. NUMERICAL STUDY

A. TEST NETWORK OVERVIEW AND BASIC SETTINGS

In this section, the proposed model is implemented on a modified version of the test distribution network connected to

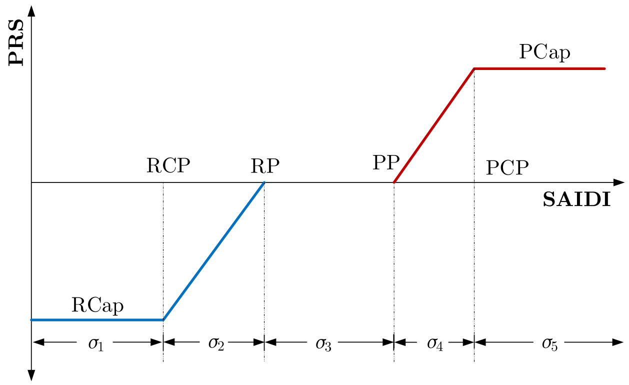

FIGURE 3. Reward-penalty graph.

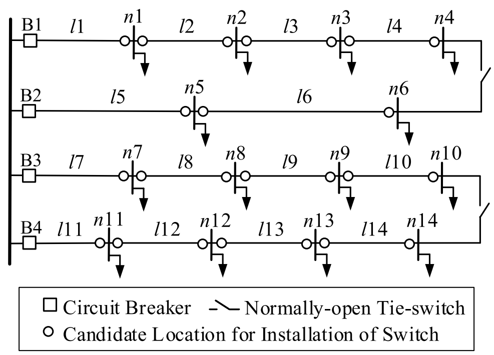

FIGURE 4. Single-line diagram of the distribution network connected to RBTS Bus 2.

bus 2 of the Roy Billinton test system (RBTS). As depicted in Fig. 4, the test network consists of 4 feeders, 14 feeder sections, 14 load nodes, and 2 tie switches.

In the implemented simulations, a planning horizon of 15 years with an 8% annual interest rate is considered. Also, the repair time for feeder sections and switching time for MSs and RCSs are assumed to be 3 h, 1 h, and 0.1 h, respectively. The investment and installation costs of RCSs and MSs are considered to be 4.7 k$ and 0.5 k$, respectively. Similarly, the operation and maintenance costs of RCSs and MSs are respectively set to 0.094 k$ and 0.010 k$ per year. In addition, the expected revenue obtained from delivering one unit of electrical energy to the customers, ρ, is considered 0.12 k$/MWh.

As for the reward-penalty scheme, the values of reward, reward cap, penalty, and penalty cap points are assumed to be equal to 0.45, 0.05, 0.50, and 0.90 of hours per customer per year, respectively. Also, the incentive reward rate and incentive penalty rate are set at 50 k$ and 30 k$ per unit of SAIDI, respectively.

To analyze the impact of the reward-penalty scheme on the optimal distribution switch investment, two cases are studied. In Case I, the reward-penalty scheme is taken into account, whereas it is eliminated in Case II. Thus, in the latter case, RRC only comprises the expected revenue lost, $\rho.EENS$. As the devised optimization model is an instance of MILP, it is readily implemented in GAMS 24.9 and solved by CPLEX 12.6 with the optimality gap set to 0.

TABLE 1. Numerical results for the distribution network connected to RBTS bus 2.

	Case I	Case II
Objective function OF (k$)	-7.079	0.857
Annualized investment cost of switches $\delta^T Inv$ (k$)	2.290	0.292
Operation and maintenance cost of switches Op (k$)	0.392	0.050
Penalty-reward cost PRS (k$)	-10.103	–
Revenue lost from undelivered energy $\rho.EENS$ (k$)	0.342	0.515
SAIDI (hours/customer/year)	0.113	0.378
EENS (MWh)	2.852	4.294

B. SIMULATION RESULTS

Table 1 represents the outcomes obtained for the two mentioned cases. As per this table, while the total investment cost of switches in Case I is significantly higher than that of Case II, the objective function, which shows the annualized total cost, is by far lower in Case I, as a result of implementing the reward-penalty scheme. Thus, it can be inferred that more switches have been installed in Case I compared to Case II to enhance the network reliability, and, as a consequence, to increase the reward value. In other words, only considering the revenue lost due to unrelieved energy, without imposing a reward-penalty scheme on the DISCO, does not provide sufficient motivations to enhance the network reliability by installing distribution switches. This is also reflected in the SAIDI value for Case II, which is more than three times of that in Case I. Accordingly, due to the implemented reward-penalty scheme in Case I, by installing several MSs and RCSs, the DISCO decreases SAIDI to 0.113 h/customer/year, which is in the reward zone of the reward-penalty graph. The enhanced network reliability in Case I is also reflected by a lower EENS value, compared to Case II. These results represent the significance of implementing incentive reliability regulations in the electricity distribution sector, which is a monopoly business requiring price and quality control regulations [18], [22], [23].

The optimal switch arrangements for Cases I and II are illustrated in Fig. 5 and Fig. 6, respectively. As per these figures, while no investment in RCSs is made in Case II, three are installed in different feeders of the network in Case I. In this case, most of the switches, either MSs or RCSs, are installed close to the supply side of the distribution feeders. This is due to the fact that when the reward-penalty scheme is applied, it is of great importance to protect the load nodes with higher number of customers, and those nodes are located near the supply side of the distribution feeders in the test network. To be more specific, due to the implemented reward-penalty scheme in Case I, decreasing SAIDI is highly essential, so the load nodes with more customers have a much higher priority to be protected from long interruptions. As a result, the RCSs are installed on the downstream side of the

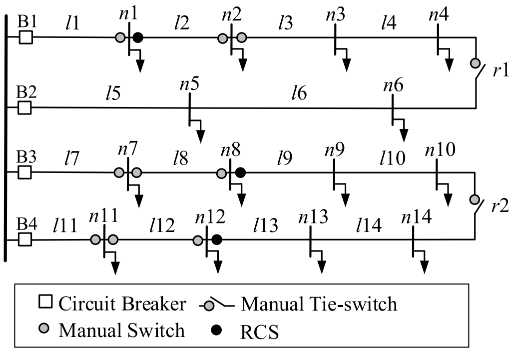

FIGURE 5. The optimal switch plan for Case I.

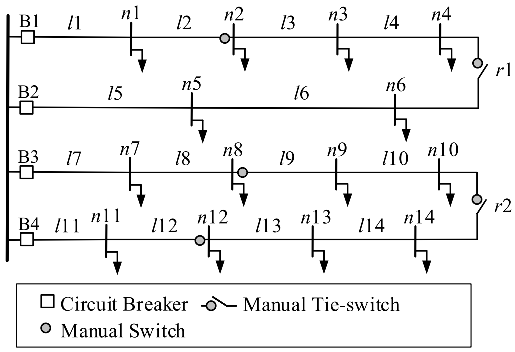

FIGURE 6. The optimal switch plan for Case II.

load nodes with over 400 customers (load nodes $n1$, $n8$, and $n12$). Consequently, when a fault occurs on the downstream feeder sections, such load nodes can be restored in the shortest possible time, i.e., the switching time of an RCS.

The reward-penalty scheme, however, does not prioritize enhancing the service reliability for the customers with significantly high power demand. For instance, load nodes $n5$ and $n6$ include one industrial customer with a relatively huge demand of 1.00 MW and 1.15 MW, respectively. Nonetheless, neither imposing the reward-penalty scheme nor considering the revenue lost due to undelivered energy provide sufficient motivation for enhancing the reliability of those load nodes. This, in turn, reflects the utmost importance of other regulatory tools, such as premium reliability contracts, to satisfy the customized quality requirements of individual customers that are not secured through system-level reliability standards [23], [25].

According to Fig. 6, in Case II, one MS is installed in the middle of distribution feeders 1, 3, and 4 so that all load nodes of these feeders can be protected from the network faults in an almost identical manner. Nonetheless, the exact locations of MSs with respect to the middle nodes $n2$, $n8$, and $n12$ are determined according to the failure rates of the upstream and downstream feeder sections of these load nodes. In this respect, the MSs are installed at the supply side of the load nodes located at the middle of feeders 1 and 4, but in case of feeder 3, on the downstream side of the load node placed at the middle of the feeder, i.e., $n8$. It can also be inferred from the locations of installed switches that decreasing the revenue lost due to undelivered energy, not SAIDI, is of importance in Case II, as expected. As a result, the number of customers connected to each load node is not critical in this case, unlike in Case I.

Furthermore, according to Fig. 5 and Fig. 6, in both of the studied cases, MSs are the optimal alternatives for the reserve connection points of the test network. Therefore, it is evident that the assumption made in [11]–[15] that the existing tie switches have a less or equal switching time in comparison to the RCSs may not be valid in every case, since the optimal choice for all tie switches might not be an RCS. As a result, deciding which switch type is appropriate for each backup location in the network should be included in the switch optimization model, as done in this paper. It goes without saying that these results, in no capacity, recommend or discourage using RCSs at the reserve connection points. However, they stress the fact that, for each distribution network, an optimization model which decides on the type of tie switches should be solved to find the most efficient type of switch for installation at those backup locations.

V. CONCLUSION

A novel mathematical programming-based model has been proposed in this paper to optimize the location and type of distribution switches under incentive reliability regulation. Incorporating a reward-penalty scheme into the model, optimizing the type of tie switches, devising a novel reliability assessment model, and deriving an innovative MILP model for the reward-penalty scheme were the main contributions of the proposed model as compared to the state-of-the-art approaches. Applying the model to a test system demonstrated the critical role of reward-penalty schemes in motivating the distribution company to enhance the service reliability. This was because of the fact that the unreliability cost in terms of revenue lost due to undelivered energy to the customers during network failures was not significant. Thus, implementing a reward-penalty scheme for the sake of managing the service reliability of distribution companies is crucial. However, it was shown that other regulatory tools might be required to address requirements of individual customers, since a reward-penalty scheme only regulates the average system reliability level. In addition, the outcomes revealed that, unlike the state-of-the-art approaches in the existing literature, the decision on the type of tie switches must also be included in the optimization model, as done in this paper.

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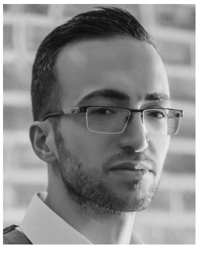

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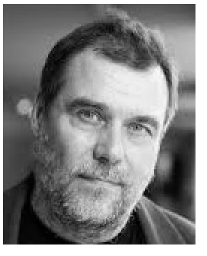

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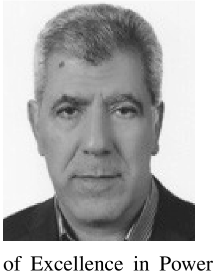

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