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RESEARCH ARTICLE

Markov-Based Reliability Assessment for Distribution Systems Considering Failure Rates

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ABSTRACT Switches (SWs) and renewable distributed generations (RDG) are subject to failure as well as other components of a system that are usually presumed fully reliable in the literature. It can lead to an overestimation of their contribution to reliability enhancement disregarding their dysfunction. This study considers the failure rate of SWs and RDGs to assess their impact on the reliability cost of the system and their effect on the optimal placement using a Markov-based approach. The optimal placement of SWs and RDGs in radial distribution systems is carried out simultaneously aim at minimizing the overall cost including investment, maintenance of SWs, and RDGs alongside the interruption cost. The performance of the model is verified through different scenarios and tested on RBTS bus 2. The results show that high values of the failure rates lead to fewer allocations to prevent plummeting the reliability of the system and increasing the capacity of the RDG results in fewer SWs allocation.

INDEX TERMS Reliability, distribution system, Markov chain, renewable resources.

I. INTRODUCTION

The end-user customers in radial distribution systems are more inclined to a higher number of outages due to the failures in upstream. These outages impose costs on both customers and the operator of the system. As a result, there should be some investment to decrease the huge costs to improve reliability. In the meanwhile, a tradeoff between the costs and investment is required to reach a minimum overall cost [1]. Sectionalizing SWs are an appropriate option that can help with outage time reduction in the downstream of a fault and the number of outages in a system [2]. It can lead to a great reduction of interruption costs of customers and reliability enhancement. So selecting the number and location of SWs turns into an optimization problem that has been considered in numerous papers in the literature [2].

In recent years, the implementation of RDGs in power systems has drawn a lot of attention that is mostly owed to environmental issues. The extension of such units has enabled them to compete in the power market [3]. Integration of renewable RDGs is turning the conventional distribution systems into active ones. RDGs such as Photovoltaic (PV) which is widely used in the system reduce the interruption cost, and outage duration regarding their fast power restoration. RDGs have the capability of improving the reliability of the distribution system and at the same time, alleviating the greenhouse emissions and fuel consumption of the conventional DGs and can enhance reliability in case of failures in terms of outage duration reduction and lost loads. These features make RDGs a suitable option for operation in the long term.

Therefore, finding the optimal location for distributed generations plays an important role in the optimization problem. However, they complicate the optimization regarding the islanded mode which is an important matter that needs to be dealt with. In [3] the impact of RDGs' presence was investigated on the optimal SW placement and locations but RDG placement was not addressed. A similar model was presented in [4] that considered RDGs' impact on optimal

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TABLE 1. **Previous works on optimal placement of SWs and DGs.**

Ref	Placement of DGs	Placement of SWs	Failure rates
[8, 12, 19-21]	No	Yes	No
[3], [15], [10, 11, 16, 18, 22-27]	No	Yes	Yes
[5, 6, 9]	Yes	Yes	No
This paper	Yes	Yes	Yes

SW placement and location but neglected RDG placement as well.

The researchers have considered different terms for the objective functions in the literature. In [5] a multi-objective problem was extended aiming at optimizing the reliability indexes by finding optimal placement and sizing of battery banks and finding optimal number and locations of SWs alongside minimizing the equipment costs. In [6] a method was presented to find the optimal placement of renewable energy-based RDGs to minimize the total cost of the system including loss minimization and RDG costs. In [7] an approach was developed to reconfigure the system in case of different failures to find the minimum outage cost regardless of the outage time. In [8] a model is presented to find the optimal size and placement of energy storage system (ESS) to enhance the reliability of the system. In () [9] a method was presented to find the optimal location of RDGs and SWs to minimize a reliability index. A model was developed in [10] to determine the type and location of the SWs aiming at minimizing the interruption cost taking installation, capital investment, and maintenance costs into account which is similar to [11]. In [12] a model was developed to find the optimal placement of protective and controlling devices in distribution systems to minimize the equipment costs alongside the interruption cost disregarding RDG.

Different reliability indices are used in the literature to find the optimal number and location of SWs in the presence of RDGs. Energy not supplied (ENS) is a suitable index to evaluate the reliability cost of the system [13]. Other reliability indices do not reflect the outage cost such as system average interruption frequency index (SAIFI) and system average interruption duration index (SAIDI) [14]. In [15] the authors proposed a multi-objective problem to minimize two reliability indices of SAIDI and SAIFI and total cost at the same time.

The effect of failure rate on system parameters and its corresponding costs are usually disregarded in the papers explained above. The authors in [16] proposed a model to examine the effects of the SWs failure in SW placement. It was shown that disregarding SWs' failure leads to an overestimation of their advantage and their placement that is an extension to [17]. In [18] a method for fault indicator placement was developed by taking the failure rate of protective SWs into account. It's worth noting that none of the above papers explaining the effect of failure rate on reliability considered RDG's presence and its effect on the reliability index and total cost of the system.

In the current paper, a Markov-based method is proposed to find the optimal placement of SWs and RDGs simultaneously while considering the effect of SWs' failure rates on the results in addition to the consideration of the failure rate of the lines.

Utilization of the Markov chain enables us to model the failure rate of SWs in the system in a deliberate mathematical way alongside the integration of RDG in the model without complicating the problem. Moreover, the unavailability of the RDG has been modeled through the proposed Markov-based method. On the other hand, in contrast to most of the papers in the literature, the occurrence of simultaneous faults is considered in the current paper. The Markov-based method presented in this paper facilitates the consideration of simultaneous faults and the failure rate of SWs without elaborating on the model. Also, regarding RDG's presence in the system, islanded mode is considered as well to reflect RDG's positive role in reliability enhancement and consequently the total cost of the system. To handle the placement of SWs and RDGs at the same time, a two-stage procedure is adopted to deal with both placements. In the first stage, the SWs are optimally placed and in the second stage, RDGs are optimally located since the location of SWs must be specified to analyze the impact of RDG on the reliability of the system. To the best knowledge of the authors (see Table 1), the optimal placement of SWs and RDGs at the same time using a mathematical solution to deal with the failure rate of SWs and RDGs hasn't been addressed in the literature, while most of the papers have utilized common solutions ignoring the possibility of simultaneous faults and the corresponding uncertainties which have been fully considered in the current paper.

Hence, the prime contributions of the paper are as follow:

1) Determining optimal placement of SWs and RGDs considering both failure rates of SWs and RDGs using Markov chain to capture the precise behavior of the RDG.
2) Evaluation of the reliability of the network by taking into account failure rate of vital components of the network (SWs and RDGs) at the same time using Markov chain to reflect their impact on the reliability considering all possible fault in the network.

The remainder of the paper is organized as follows.

In section II, the literature review is given, in section III materials and methods are explained. In section IV, the case study is described. Results are expressed in section V in finally, in section VI, conclusion are discussed.

II. LITERATURE

The current paper aims at optimal planning in distribution systems in terms of reliability, investment, and maintenance costs. Markov chain is used as a tool to evaluate the reliability of the system as a meticulous mathematical model to capture the behavior of the elements included in the system. The proposed model enables us to consider all the possible scenarios as well as their occurrence probability. The main purpose of the current paper is to find the optimal number and location of sectionalizing SWs and placement of RDGs to minimize the total cost including customer reliability costs. In contrast to pieces of research in the literature, ENS is postulated as the main reliability criterion to evaluate the cost of lost loads in the system. Furthermore, to decrease the computational burden of reliability evaluation, the system is turned into several zones and instead of dealing with a great number of elements [28], the system is down to a few elements. This technique greatly helps with the time required to run the analysis. Islanded mode operation is also incorporated in the reliability evaluation to reduce the lost loads and consequently the outage cost imposed on the operator of the system and the customers. Besides, the failure rate of SWs is regarded to consider this parameter's effect on reliability. It should be mentioned that the radiality of the system must be maintained implying that the system's elements are in series. At last, the system is configured in a way that leads to the minimum reliability cost by selecting the optimum number and location of SWs and RDGs.

A. ZONE FORMATION

In general, the presence of protection SWs in different lines leads to dividing the system into multiple zones. In a radial distribution system, n SWs at the main feeder form n zones which eases reliability evaluation of the system since the number of the elements involved decreases to a much fewer number of elements. In case of failure in the lines within the corresponding zone, the entire zone is down since there are no sectionalizing SWs to isolate the fault. Therefore, all the load points within a zone experience the same level of reliability [29]. Since the system is assumed to be radial, the components of the system are in series and the corresponding failure and repair rate of the zones are determined as follows in (1-2) [29]:

$$\lambda_{\mathrm{eq}} = \sum_{\mathrm{i=1}}^{\mathrm{n}} \lambda_i \tag{1}$$

$$\mathrm{r_{eq}} = \frac{\sum_{i=1}^{n} \lambda_{\mathrm{i}} \times \mathrm{r}_i}{\lambda_{\mathrm{eq}}} \tag{2}$$

where λ_{i} and $\mathrm{r_i}$ are the failure, and repair rates of component i. In general, the outage of a zone in a radial system leads to the outage of the rest of the system downstream of the outage unless there is a generation source that can feed the loads. Therefore, ENS due to a certain outage equals the load of the interrupted zone and the downstream of that outage minus the friction of the loads that can be recovered. This is true for a single outage in the system. In the case of simultaneous outages in the system, the system may be divided into multiple islanded zones that might be separate from each other that are not connected directly. In this case, the disconnected zones can only be operated if there is a generation source in that zone or the adjacent connected zones. It means in a large system with several zones, the occurrence of several outages creates several isolated and connected zones that the connected zones are operated together via the generation source within at least one of those connected zones. The zones isolated from the other zones with no generation source would experience an outage. Therefore, the ENS of the system is the summation of all possible outages with their corresponding probability multiplied by the corresponding loads as shown in [28].

B. CLUSTERING TECHNIQUE

To deal with the successful operation of islanded zones, the loads and the generation outputs need to be divided into a certain number of clusters using a clustering technique to decrease the vast amount of data. The number of clusters has a direct relationship between the accuracy and the numerical evaluation duration and it can vary regarding the number of data available for both generation output and the loads.

$$\begin{aligned}\mathrm{P_{island}} &= \sum \mathrm{Prob}(\mathrm{P_{max}} \geq \mathrm{load}_c) \\ &= \sum (\mathrm{P}\{\mathrm{output}\} \times \mathrm{P}\{\mathrm{load}\})\end{aligned} \tag{3}$$

$\mathrm{P_{island}}$ is the probability of successful operation in case of an outage (outages) which is a function of generation capacity and the isolated load within the isolated zone. $\mathrm{P_{max}}$ is the maximum capacity of the generation source and load_c denotes the load of the c-th cluster. The first step is to divide loads into a certain number of clusters and the available generation as well due to the intermittency of the output of PV. Actually, regarding the load curve of each customer in a certain study period and according to the available capacity of RDG, loads of the system are divided into several clusters. The clusters are listed in descending order from the peak load to the minimum level of load and the corresponding probability of each cluster is determined. According to the available capacity of the RDG, the probability of the cases where the generation level exceeds or equals the load level in a period study are aggregated that results $\mathrm{P_{island}}$. In (3), $\mathrm{P}\{\mathrm{output}\}$and $\mathrm{P}\{\mathrm{load}\}$ denote the probability of the PV to generate power equal or higher than a certain level and the probability of a load with a certain level.

Regarding the intermittent output of renewable energy resources, the probability function is hard to determine.

Therefore, a statistical approach based on the historical data of renewable resources is adopted to deal with this issue. The final $\mathrm{P_{island}}$ is the average value of all successful probabilities considering the PV outputs [26]. In the following sections, $\mathrm{P_{island}}$ used in the equations are determined by (3) which considers all the throughout the study period.

$$\mathrm{P}_{Pisland}^{average} = \sum_{d=1}^{N_{data}} \frac{\mathrm{P_{island}}}{N_{data}} \tag{4}$$

In which d denotes the data index and $N_{data}$is the number of data available. It should be mentioned that similar to clustering the loads, the PV output is clustered into a certain number of clusters and the probability of each cluster is calculated. The probability of each cluster shows what percentage of the loads is higher than a certain value [28].

C. MARKOV CHAIN-BASED MODEL

Markov chain is a mathematical tool among the various methods that are applied to reliability evaluation considering the zo nes of the system as components with equivalent failure and repair rates. In [26] Markov model was utilized to integrate an energy system in the distribution system to analyze the reliability of the system. Generally, the systems are first simplified to reduce the computational burden. Using the Markov model, all possible states of a system is listed and the ENS of the system is determined based on the characteristic of the system's components. It's also noteworthy that according to (1), the equivalent failure rate of a feeder is constant but based on the location of the SWs and the equivalent failure and repair rates of the zones, the corresponding probability of the states is highly dependent on the location of the SWs. Therefore, it can greatly affect the resultant ENS of the system. For a two-zone system implying that there is one SW between the zones, there are four states shown in Figure 1. The ENS of a two-zone system with an RDG located at zone 2 is as follows:

$$\begin{aligned} ENS = {} & [P_2 \times (L_1 + (1 - P_{island}) \times L_2) \\ & + P_3 \times L_2 + P_4 \times (L_1 + L_2)] \times 8760 \end{aligned} \tag{5}$$

$\mathrm{P_{island}}$ used in (5) is actually the final probability of successful operation of RDG in the islanded zone which is extracted and determined by (4) that includes all the data available for the reliability evaluation in the study period.

The probability of each state can be extracted through (6) and (7).

$$\begin{aligned} & \begin{bmatrix} P_1 & P_2 & P_3 & P_4 \end{bmatrix} \\ & \times \begin{bmatrix} 1-\lambda_1-\lambda_2 & \lambda_1 & \lambda_2 & 0 \\ \mu_1 & 1-\mu_1-\lambda_2 & 0 & \lambda_2 \\ \mu_2 & 0 & 1-\mu_2-\lambda_1 & \lambda_1 \\ 0 & \mu_2 & \mu_1 & 1-\mu_1-\mu_2 \end{bmatrix} \\ & = \begin{bmatrix} P_1 \, P_2 \, P_3 \, P_4 \end{bmatrix} \end{aligned} \tag{6}$$

$$P_1 + P_2 + P_3 + P_4 = 1 \tag{7}$$

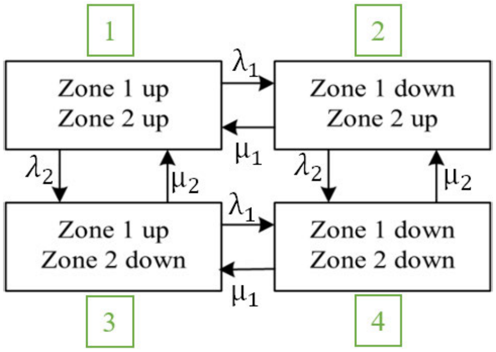

FIGURE 1. Markov chain states of a two-component system.

In the case of a two-zone system, the outage of zone 1 - state 2- leads to the outage of zone 1 and zone 2. Zone 2 can be restored by the factor of $(1 - P_{island})$since there is an RDG in zone 2. P_{island} is the probability of zone 2 to be successfully operated. The Outage of zone 2 - state 3 - only results in the outage of zone 2 and finally, the outage of zone 1 and zone 2 - states 4 - causes to lose of both zones. L_1 and L_2 are the average loads of zone 1 and zone 2 respectively and $P_i$denotes the probability of each state specified in Figure 1. As mentioned earlier, the multiple outages of the zones are also considered. In the case of a two-zone system, state number 4 stands for the simultaneous outage of both zones, therefore, the multiple outages of zones can be considered in the proposed model that is neglected in most of the researches in the literature.

III. MATERIALS AND METHODS

In any system with any kind of formation, series, or parallel, the components are subject to failure with a certain failure rate that indicates the average number of failures in a certain period. Usually, the failure rate of a component following exceptional distribution is assumed constant, which is dependent on time to simplify the problems and avoid unnecessary complexities [29]. In this paper, in the following sections, the modeling of their failure in the proposed Markov chain framework is explained.

A. SWs FAILURE RATE

Since the SWs used to form the zones are not fully reliable and are subject to failure based on their failure rate, they can be considered in the reliability evaluation. Similar to the equivalent failure and repair rates of the zones, a failure rate, and a repair rate are assumed for the SWs. Regarding the radiality of the system, the SWs are formed in series with other components –known as zones- of the system and also can be treated as zones without loads (assigning zero for the load of the corresponding zone). To distinguish the difference in consideration of SWs' failure rates, the system explained in section IV is described. Since there are two zones in the system, it implies that there is one SW between zones 1 and 2 considering the circuit breaker at the beginning

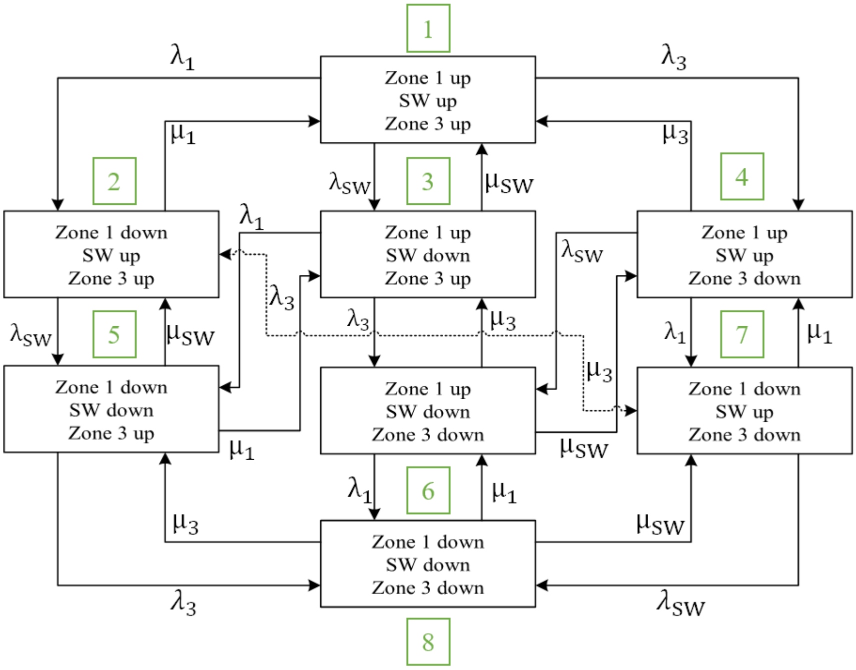

FIGURE 2. Markov chain states of a three-component system.

of the system is assumed fully reliable without loss of generality. Therefore, a two-zone system turns into a three-zone system by taking the failure rate of SWs into account. Similar to the states depicted in Figure 1, the states of a three-zone system can be extracted as well shown in Figure 2 and the outcome of the system is shown in Figure 3.

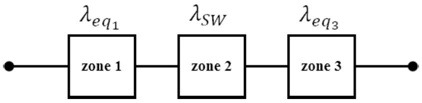

FIGURE 3. The equivalent Markov model of a system with one SW.

Given the configuration of a three-zone system shown in Figure 3, the total number of states for a three-zone system is 8 and the ENS is obtained as depicted in (8):

$$\begin{aligned} ENS = {} & [P_2 \times (L_1 + (1 - P_{island}) \times L_3) \\ & + P_3 \times (1 - P_{island}) \times L_3 + P_4 \times L_3 \\ & + P_5 \times (L_1 + (1 - P_{island}) \times L_3) \\ & + P_6 \times L_3 + P_7 \times (L_1 + L_3) \\ & + P_8 \times (L_1 + L_3)] \times 8760 \end{aligned} \tag{8}$$

To elaborate on the obtained equation on ENS of a three-zone system, some explanations are needed to illuminate the issue. In the case of a three-zone system, an outage in zone 1 leads to an outage in zones 2 and 3. Since it's assumed that there is an RDG located at zone 3, zone 3 can be fed through that. The Outage of zone 2 - the zone representing the SW- causes the isolation of zone 3 which also can be supplied by the RDG. Since the second zone contains no load, then its outage only affects the third zone. In (8), P_{island} is the probability of zone 3 to being operated successfully. Similar to the two-zone system, state 8 indicates the case where all three zones encountered with an outage.

B. RDG FAILURE RATE

In addition to consideration of the failure rate of SWs, the RDGs are also subject to failures that need to be taken into reliability evaluation account. To the best knowledge of the authors, the effect of malfunction of RDG is modeled through (9). The probability of successful operation of islanded zones is multiplied by the factor of (1-FOR) [3] in which FOR denotes the forced outage rate of RDG.

$$\mathrm{P_{island}} = \sum (\mathrm{P\{output\}} \times \mathrm{P\{load\}}) \times (\text{1-FOR}) \tag{9}$$

In this paper, the malfunction of RDG is modeled through the Markov Chain as well as the other components of the system in a deliberate mathematical way. To integrate the role of the malfunction of RDG in the system, the system in the previous section is modified in the following. An RDG located at a zone is parallel with its corresponding zone which is vital to the zone in case of an outage in the upper hand of the zone that is modeled in Figure 4. Similar to the modeling of failure of SWs, the failure of an RDG is also incorporated into the reliability evaluation of the system. For the system illustrated in Figure 4, RDG is regarded as a new component and as a result, the Markov states shown in Figure 6 increase from 8 to 16 in the following.

The difference between modeling the failure rate of SWs and the failure rate of RDG is that in the first case, all

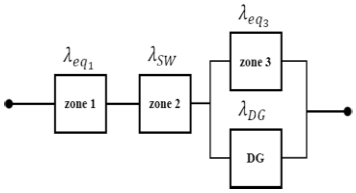

FIGURE 4. **The equivalent Markov model of a system with one SW and an RDG.**

components are in series while in the second one, the introduced component is in parallel with the equivalent component (zone). Similar to the states shown for the failure rate of SWs, all possible states for the new case can be determined as well with one important difference. The unavailability of the RDG would not necessarily lead to the outage of its corresponding zone while in the previous case, outage of a SW causes an outage in the lower hand of the SW due to the series form of the zones. The outage of RDG leads to the interruption of the corresponding zone if the zone is isolated and can only be fed through the RDG – states 10 and 11. In a case where only RDG experiences an outage and the rest of the system is available, no lost load is incurred to the system– state 5-. It's also worth mentioning the entire load of a faulty zone is lost even if the RDG is available –state 4. The ENS of the system considering the failure rates of SWs and RDG can be determined through (9):

$$\begin{aligned}ENS = {} & [P_2 \times (L_1 + (1 - P_{island}) \times L_3) \\ & + P_3 \times (1 - P_{island}) \times L_3 + P_4 \times L_3 \\ & + P_6 \times (L_1 + L_3) + P_7 \\ & \times (L_1 + L_3) + P_8 \times (L_1 + L_3) \\ & + P_9 \times L_3 + P_{10} \times L_3 \\ & + P_{11} \times L_3 + P_{12} \times (L_1 + L_3) \\ & + P_{13} \times (L_1 + L_3) + P_{14} \times (L_1 + L_3) + P_{15} \times L_3 \\ & + P_{16} \times (L_1 + L_3)] \times 8760 \qquad (10)\end{aligned}$$

A similar procedure applied to a two-component system in (6) and (7) can be extended to determine the probability of each state shown in Figure 5. The model explained in this section presents a thorough modeling of failure rate and repair rate of an RDG's malfunction while in [3] and most of the papers in the literature it was overlooked and simplified that didn't capture the exact behavior of RDG's malfunction.

SW allocation is the main key in reliability enhancement in the system that pushes the system toward better reliability service to the customers. The relation between reliability and its corresponding costs is shown in Figure 5.

However, as can be seen in Figure 5, as the system costs including SW investment cost grows, the reliability of the system declines as well as the customer outage cost. To gain the maximum advantage out of SW employment in the system, a trade-off has to be established between the costs and reliability. System costs shown in Figure 6 can include any kind of costs that are imposed on the system operator. First, the different parameters have to turn into the same dimension to enable us to carry out the SW allocation. To this end, the reliability is transformed into reliability cost to reflect the reliability effect on the total costs.

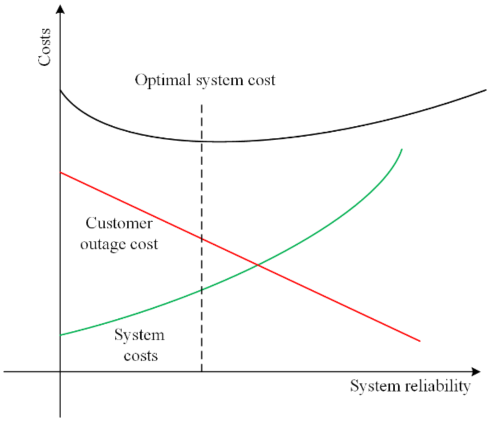

FIGURE 5. **Cost curves as a function of reliability and optimal system cost.**

C. UNCERTAINTY MODELING

Due to the forecasting of loads, uncertainty in their values can cause the deviation of optimal solutions. In this paper, to consider the possible deviations in loads, normal distribution has been used [30], [31], [32], [33], [34]. According to this method, the normal distribution is divided into seven parts in which the area of each part indicates the probability of the average load of the corresponding part. The amount of expected ENS equals the summation of multiplying the value of the ENS computed by the proposed Markov Chain method and the probability of the ENS being presented in that part. For the normal distribution shown in the Figure 7, δ denotes the maximum deviation from the mean value μ.

D. OBJECTIVE FUNCTION

The total cost (TC) is the summation of all costs regarding SW, RDG and outage cost that are expressed through the following equation.

$$TC = SC + DGC + \sum_{t=1}^{T} OC \times (1 + \sigma)^{t-1} \qquad (11)$$

In (11), σ indicates load growth. The different terms of costs are listed in detail as follows:

1) SW COST

The SW cost (SC) is a combination of three terms including installation cost (IC), capital investment cost (CC) and maintenance cost (MC) that is formulated as follows:

$$\begin{aligned}TC = {} & \sum_{j=1}^{N_{SW}} \sum_{f=1}^{N_f} (IC_j + CC_j) \times X_{j,f} \\ & + \sum_{j=1}^{N_{SW}} \sum_{t=1}^{T} \sum_{f=1}^{N_f} MC_{t,j} \times X_{j,f} \qquad (12)\end{aligned}$$

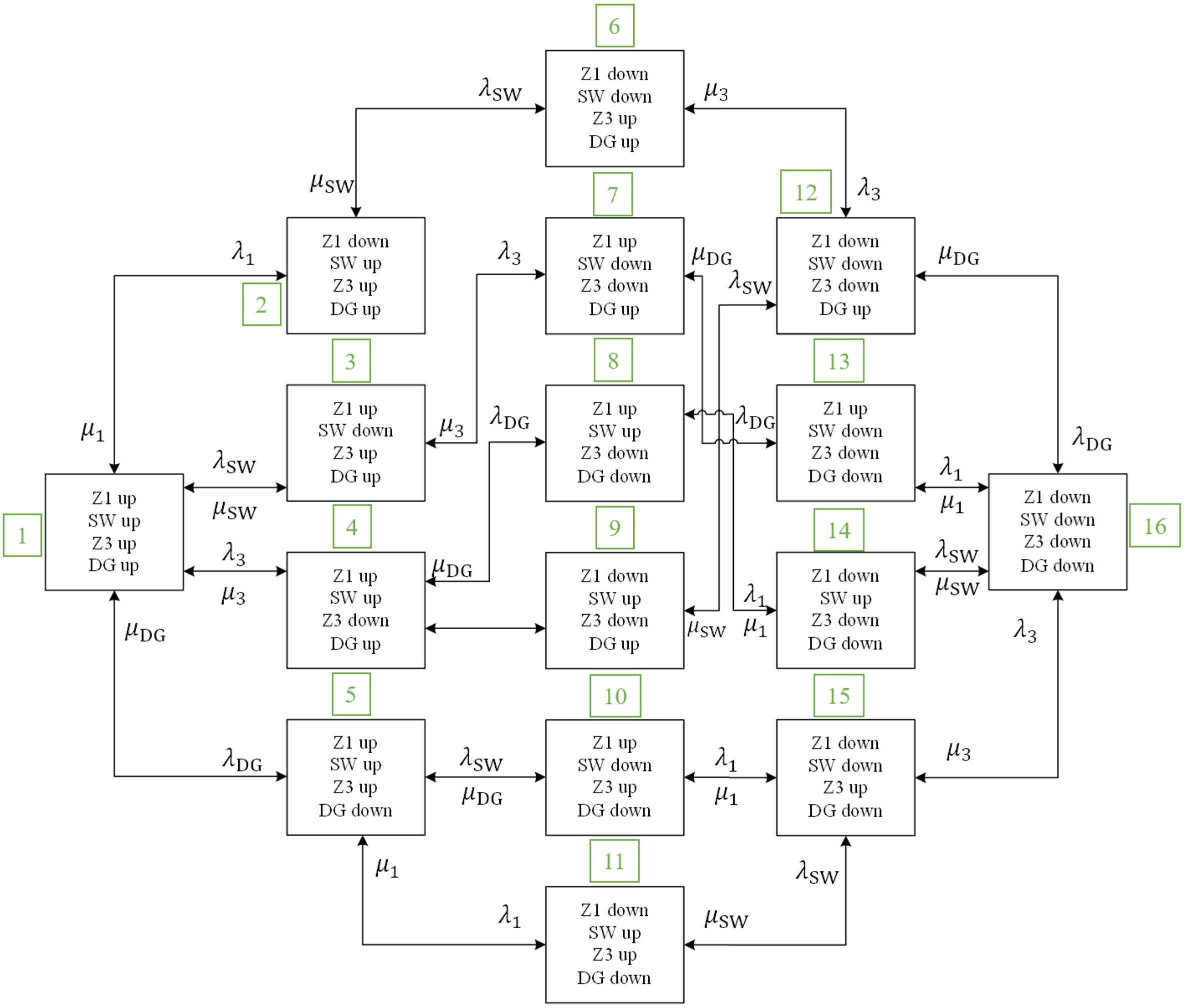

FIGURE 6. Markov chain states of a four-component system.

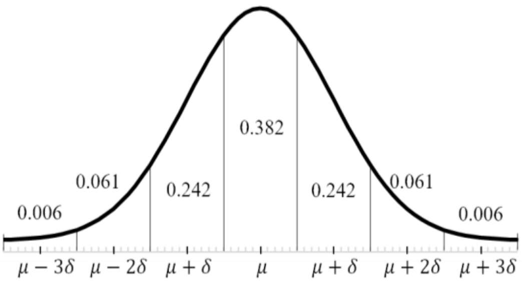

FIGURE 7. Approximation of the seven-step of the normal distribution.

where j and t denote the SW and time respectively. $X_{j,f}$ indicates the binary variable of SW existence at feeder f. If $X_{j,f}$ is set to 1 it shows that the SW is placed at feeder f and otherwise, $X_{j,f}$ =0. In addition, the number of SWs is limited to $N_{\max}$ that equals the number of possible locations assumed for each feeder.

$$\sum_{j=1}^{N_{SW}} X_j \leq N_{\max} \tag{13}$$

2) RDG COST

The cost of an RDG (RDGC) is consisted of two terms including investment and maintenance that is shown as follows:

$$RDGC = \sum_{k=1}^{N_{DG}} \sum_{z=1}^{N_z} (CC_k + IC_k) \times Y_{k,z} \tag{14}$$

where k and N_{DG} the index of RDG and number of RDGs in the system respectively. $Y_{k,z}$indicates the binary variable of RDG existence at zone z. If $Y_{k,z}$ is set to 1 it shows that the RDG is placed at zone z and otherwise, $Y_{k,z} = 0$.

The capacity of the RDG is assumed 0.2 of the summation of the total load of each feeder which is shown as follows:

$$\mathrm{P}_{\max} = 0.2 \times \sum_{\substack{m=1 \\ m \in f_l}}^{M} Load_m \tag{15}$$

In which m and M denote the customer index and the number of customers in the feeder and l is the feeder index, respectively.

3) OUTAGE COST

In the current paper, the outage cost (OC) of customers is assumed as a constant value which is known as the value of lost load (VOLL). The outage cost of each feeder is the product of VOLL and its corresponding ENS. The total outage cost of customers in the system is as follows:

$$OC = \sum_{m=1}^{M} (ENS_m) \times VOLL \tag{16}$$

E. SOLUTION PROCEDURE

Binary particle swarm optimization (BPSO) is a binary form of the PSO presented to solve related issues. BPSO has been vastly employed in different problems of power system optimization regarding its proper performance in the literature [35]. Similar to PSO, the velocity of a particle is updated as a combination of personal best and global best. Focusing on the performance and the efficiency of the optimization algorithm utilized in the paper is beyond the main goal of this paper. Therefore, please refer to the related paper [36] for more information about the BPSO algorithm.

The simulation of the proposed model is carried out through a nested BPSO which is consisted of two BPSO optimizations. The first one is related to the SW placement while the second one deals with the RDG placement which the entire optimization procedure is summarized as follows:

IV. CASE STUDY

In this section, the performance of the presented method is analyzed by implementing a radial distribution system connected to Bus 2 of the Reliability Busbar Test System (RBTS2). The system consists of 22 load points and 14 SW locations assumed to be possibly placed at the beginning of each line. The utilized SWs in the current study are considered manual. The information needed in the simulation including average loads, failure, and rate repair rates is extracted from [37]. The failure rate of each line is assumed 0.13 f/km.yr, the repair time is 5 hr, and the system data of RBTS2 is depicted in Table 2. The failure rate and repair time of the RDG is 0.04 f/yr and 18.25 hr [38]. The load growth is assumed 7%. The capital investment cost of SWs is assumed \$ 500 [25] and the maintenance cost is assumed 2% of the capital investment cost [22]. The failure rate of SWs is assumed 0.05 [25] and the VOLL is set to 5.5 \$/KWh [39]. The study period is 15 years and the RDG capacity at each feeder equals 0.2 of the total load of the corresponding feeder. Also, the capital investment cost of an RDG is assumed to be 1880 \$/KVA and the maintenance cost is 2% of the capital cost, respectively. Finally, the presented model is simulated in MATLAB 2015b. Multiple cases are considered to indicate the efficiency of the proposed model. The case where the failure rates of SWs are neglected and they operate fully reliable is postulated as the base case. In another case, a failure rate of 0.05 is assumed for each SW which denotes the probability of SW malfunction. The optimal location of SW, the ENS, the total cost, and the optimal location of RDGs in these two cases implemented on RBTS2 are presented in Tables 3, 4, and 5 respectively. Also, the resultant configuration of the system considering the failure rate of SWs is illustrated in Figure 8.

Algorithm 1 Algorithm to the Simultaneous Placement of SWs and RDGs Regarding Their Failure Rates.

```
    Input: calling system data for external BPSO
    algorithm (line length, peak and average loads,
    failure rates)
    While ($f$ < number of feeders) do
        Tuning of constriction coefficient parameters for
        feeder $f$
        Generating initial population for possible
        positions of SWs for feeder $f$
        Calculating the number of zones, their loads,
        failure, and repair rates based on Eq. (1-2) for
        feeder $f$
        Considering deviation of zone loads according to
        uncertainty modeling section for feeder $f$
        Calculating the probability of Markove states
        according to section IV for feeder $f$
        Input: number of zones, their loads, failure, and
        repair rates for internal BPSO algorithm
        While ($z$ < number of zones) do
1           Tuning of constriction coefficient parameters
2           Generating initial population for possible
              positions of RDG
3           Evaluating the RDG cost function (Eq. (14)),
              the personal, and global best
4           Updating the velocity and positions of
              particles
5           Converged?
6           If yes break, otherwise go to step 11
        Calculating $P_{island}$ (Eq. (3))
7       Calculating ENS for feeder $f$ according to
          section V
8       Multiplying ENS and the corresponding
          probabilities according to uncertainty modeling
          section for feeder $f$
9       Evaluating summation of the outage, RDG, and
          SWs costs, the personal, and global best
10      Updating the velocity and positions of particles
11      Converged?
12      If yes, continue, otherwise go to step 3
13      All feeders are considered?
14      If yes, end, otherwise $f = f + 1$, then go to step 1
```

V. RESULTS AND DISCUSSION

Based on the optimal solution in Table 3, different zones can be formed such as the schematic depicted in Figure 8. Also, according to Table 4, the total ENS of the system shows an increase of 7% in the case of malfunctions. Similarly, the total cost of the system increases by 6.7% in case of considering

TABLE 2. System data of RBTS 2.

Line (#)	Line length (km)	Average load (MW)	Peak load (MW)
1	2.15	1.07	1.7336
2	2.15	1.101	1.7835
3	2.3	1.111	1.6667
4	1.4	0.454	0.75
5	1.55	1	1.6279
6	1.4	1.15	1.8721
7	1.35	0.535	0.8667
8	2.35	0.985	1.5959
9	2.15	1.132	1.8334
10	1.35	0.454	0.75
11	2.15	0.904	1.4791
12	2.15	0.9	1.4582
13	1.55	0.566	0.9167
14	2.15	1.132	1.6667

TABLE 3. The optimal locations of SWs.

Feeder	Lines
1	2,3,4
2	6
3	8,9,10
4	12,13,14

TABLE 4. The ENS of each feeder for 15 years.

Feeder	ENS (MWh)	
	Without failure rates of SW & RDG	With failure rates of SW & RDG
1	463.7	485.9
2	131.4	153.3
3	378.2	427.8
4	458.7	468.9
Total	1432	1535.9

failure rates. The optimal placement of RDGs, which are all located at the latter zone of their corresponding feeder, is not affected in the case of malfunctions in comparison to the fully reliable function of SWs and RDGs.

According to Table 5, although failure rates increase the outage possibility and therefore ENS, they do not have an impact on the number of SWs and RDGs since the more SWs and zones, the more reliable operation of the system will be reached. The optimal placement of RDGs for each feeder is illustrated in Table 6. The location of RDGs in the feeders maintains the same in both cases with, and without failure rates. It is related to the fact that placing an RDG with a capacity of 0.43 MW (0.2 of the total load of the feeder) imposes more cost than the reliability cost inflicted on the system. The generation level of RDG is lower than each load at each time interval of the study. According to Table 2, the average load of zone 5 (load point 9) is 1.15 MW and RDG is not able to supply the load within zone 5, and as a result, the P_{island} is zero and the presence of RDG in this feeder is not beneficial. The Total average load of this feeder is 2.15 MW and since there are two possible locations for SW placement, no RDG is selected for this feeder. Similar to Table 3 regarding the location of SWs, the location of DGs remains unchanged and it has not been reported in Table 6. Different sensitivity analysis is carried out to validate the performance of the proposed model. It can be divided into several scenarios to consider the effect of different parameters of the model on the outcome.

A. SCENARIO 1) THE EFFECT OF RDG CAPACITY ON ENS

To evaluate the impact of RDG capacity on the outcome of the model in case of SW malfunction, the capacity of RDG is increased from 0.2 of each feeder's load to 0.8. As can be seen in Figure 9, increasing the capacity of RDG leads to a decrement of ENS in each feeder. Also, it is shown that increasing the capacity to 0.5 has no impact on the ENS of feeder 2 since even the higher capacity of RDG (0.5 of the total load of the feeder) is not high enough to supply the demand of feeder 2. Increasing RDG capacity results in a reduction in optimal numbers of SWs and consequently, the number of zones. This can be seen in Table 7 where the optimal number of SWs is decreased by 2 and therefore the number of the optimal zones is reduced from 4 zones to 2 zones. It stems from the fact that increasing RDG capacity can compensate for the ENS deterioration as a result of employing fewer SWs.

As can be seen from Tables 7-8, the capacity of the RDG plays a vital role in SW allocation in the system. The number of SWs allocated to the system shows a meaningful decrease as it is reduced from 10 SW to 4 in the system. In fact, the higher capacity of the RDG supersedes the allocation of a higher number of SWs in the system to keep the ENS at a lower level. The effect of the ENS (and also other distribution reliability index such as SAIDI and SAIFI) reduction is significant due to the increase in the capacity of RDG. All the feeders in the system show the same behavior as the capacity of the RDG gets higher. Lowering the cost of the DGs regarding the new technologies can reduce the RDG cost in addition to the outage cost reduction and SWs costs.

B. SCENARIO 2) EFFECT OF FAILURE RATE ON SOLUTIONS

In Figure 10, the effect of the increasing failure rate of SWs on total outage cost is depicted. As can be perceived, increasing the failure rate of the SW leads to the increment of outage cost since the worth of allocating SWs to improve the reliability of the system diminishes.

As an example, for feeder 4, the effect of the failure rate on ENS on this feeder is shown in Figure 11. As can be seen, increasing the probability of SW malfunction significantly deteriorates the reliability index of the system. The ENS variation of the system for different SW failure rates is depicted in Figure 11.

TABLE 5. Total cost (for 15 years).

Feeder	Cost of the system ($)					
	Without failure rates			With failure rates		
	ENS cost	SW costs	RDG costs	ENS cost	SW costs	RDG costs
1	3891738	1950	3056344	4077983	1950	3056344
2	1102851	650	1802757	1287241	650	1802757
3	3173914	1950	2594220	3590383	1950	2594220
4	3850258	1950	2834811	3935966	1950	2834811
Total	12018761	6500	10288132	12891573	6500	10288132

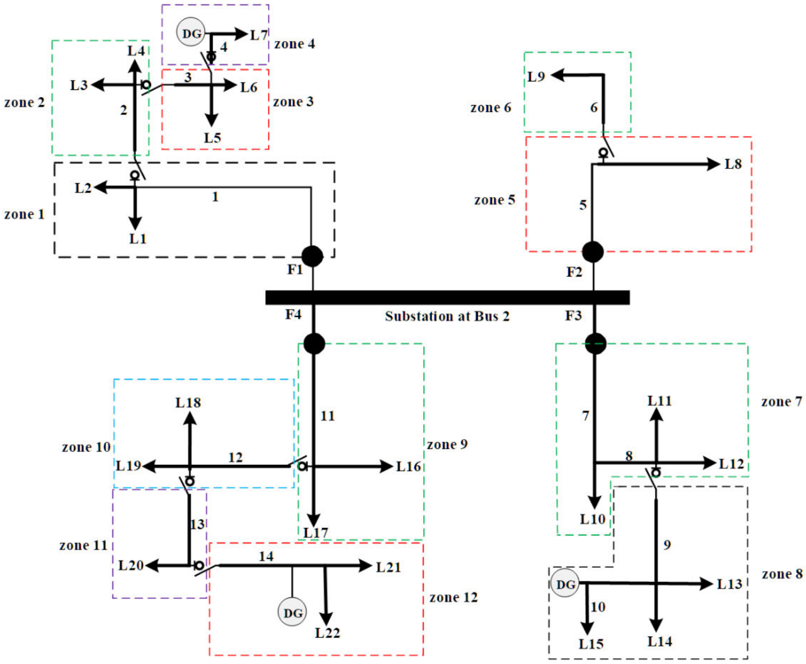

FIGURE 8. The final configuration of the RBTS2 system considering SW failure rate.

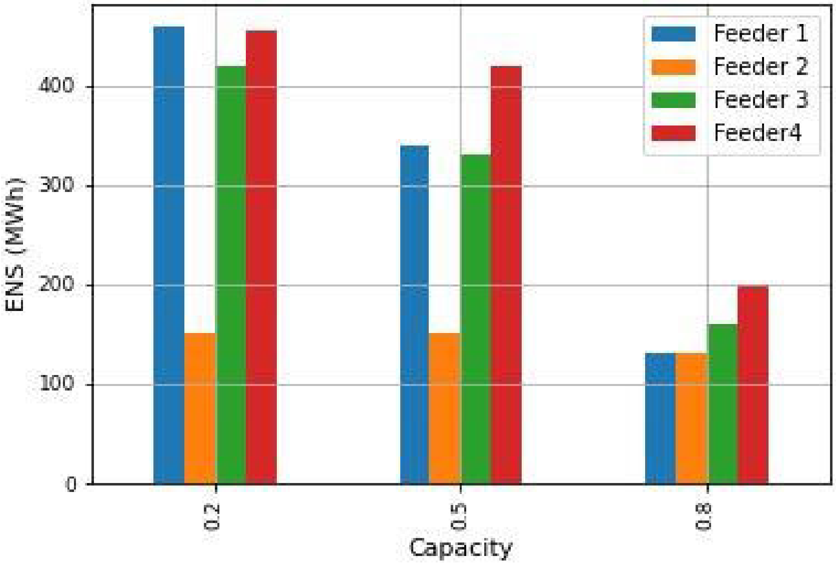

FIGURE 9. The effect of RDG capacity on the ENS of each feeder.

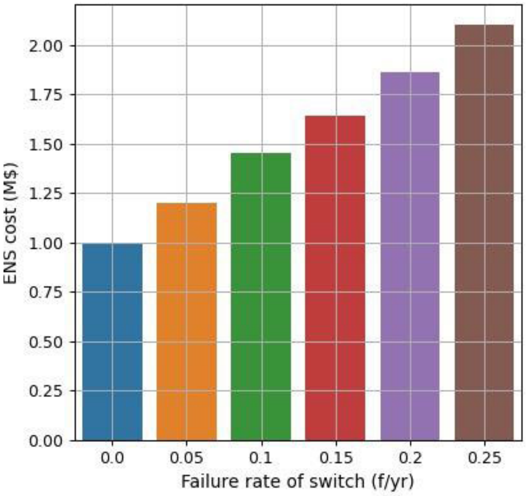

FIGURE 10. The effect of failure rate on outage cost (for 15 years).

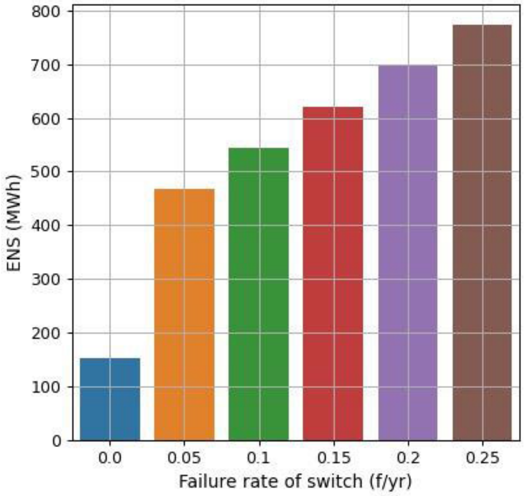

FIGURE 11. The effect of SW failure rate on ENS of feeder (for 15 years).

TABLE 6. The optimal location of RDGs.

Feeder	RDG location	
	Without failure rates of SW & RDG	With failure rates of SW & RDG
1	4	4
2	-	-
3	10	10
4	13	13

According to Figure 12, generally, as the failure rate of SWs increases the number of SWs allocated to the system decreases (from 3 SWs to 2 SWs). It shows that despite increasing the failure rate of SWs, the system tends to allocate SWs to prevent the ENS from deteriorating to a lower level. For that purpose, it is shown that for a specific failure rate (0.2), how the ENS of the feeder is affected by the SWs allocated in the following table.

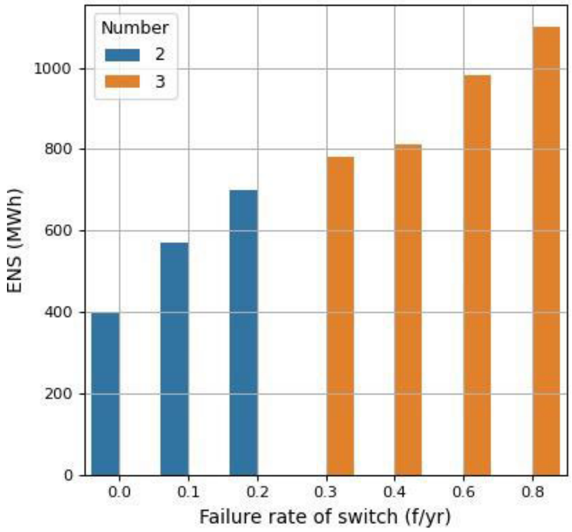

FIGURE 12. The effect of the failure rate of SWs on ENS and number of allocated SWs (for 15 years).

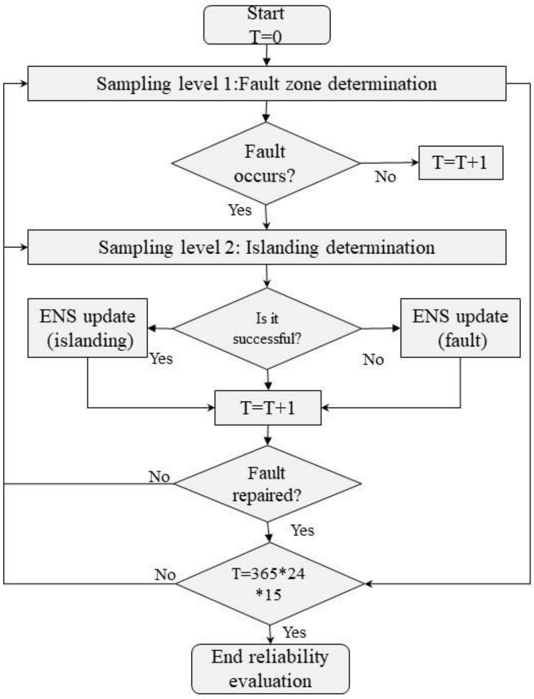

FIGURE 13. Monte Carlo simulation for reliability evaluation.

According to Table 9, different scenarios of SW allocation are considered and the results show that the fewer SWs are allocated, the higher the ENS becomes. Therefore, even by considering the failure rate of SWs, the system does not reduce the number of SWs. Past a certain value for the failure of SWs (0.22), the failure rate of SW supersedes its benefit and pushes the system towards allocating less number of SWs to keep the ENS as low as possible.

TABLE 7. **The effect of the capacity of RGD on different parameters (capacity 0.2).**

feeder	ENS (MWh)	SAIFI (Intr/cust-yr)	SAIDI (hrs./cust-yr)	ENS cost ($)	Number of SWs	SWs costs ($)	RDG costs ($)
1	485.8	0.56	8.78	4077983	3	1950	3056344
2	153.3	1.11	4.79	1287241	1	650	1802757
3	427.7	0.58	9.05	3590383	3	1950	2594220
4	468.9	0.59	9.02	3935966	3	1950	2834811

TABLE 8. **The effect of the capacity of RGD on different parameters (capacity 0.6).**

feeder	ENS (MWh)	SAIFI (Intr/cust-yr)	SAIDI (hrs./cust-yr)	ENS cost ($)	Number of SWs	SWs costs ($)	RDG costs ($)
1	186	0.21	3.36	1561771	1	650	5434696
2	131.3	0.95	4.12	1102743	1	650	5408273
3	128.8	0.17	2.72	1081137	1	650	3795990
4	153	0.19	2.94	1287579	1	650	4512045

TABLE 9. **The ENS of the feeder 4 for different SWs' allocation.**

SW location (line)	ENS (MWh)
13,14,15	697
14,15	713
15	722
13,15	786

TABLE 10. **Comparison results of proposed model and Monte Carlo for ENS index.**

feeder	ENS (MWh)
1	411
2	146
3	385
4	423

C. SCENARIO 3) VALIDATION

In this section, the proposed model is simulated and compared by the Monte Carlo approach to validate the numerical results. In this regard, a fault event is generated with the random number F based on the failure rate of each zone, and in each iteration. Using (17), the fault area is determined and the ENS is calculated according to section III and Fig 13. 2000 samples are generated and their expected values are reported in Table 10. Comparing the results of this table and Table 7 shows how close they are.

$$\text{Faulty zone} = \begin{cases} 1 & 0 \leq F < \lambda_1 \\ 2 & \lambda_1 \leq F < \lambda_1 + \lambda_2 \\ \cdots & \\ k & \sum\limits_{i=1}^{k-1} \lambda_i \leq F < \sum\limits_{i=1}^{k} \lambda_i \\ None & \text{else} \end{cases} \tag{17}$$

VI. CONCLUSION

In this paper, a Markov-based method was developed to simultaneously optimize the placement of SW and RDG in a radial distribution system in a two-level optimization considering the uncertainty of loads. The failure rate of SWs was considered to analyze how they affect the planning. The RDG optimal placement was also carried out in the paper and the effect of its capacity was also investigated. The placement of RDG could be carried out once the SW placement was fulfilled due to the dependency of the impact of RDGs on the location of SWs that was managed by utilizing a two-stage optimization. To show the effectiveness of the optimization problem, the model was also simulated by Monte Carlo and the results revealed that the performance of the proposed model. The main points can be raised in the proposed method as follows:

1) The failure of SWs led to imposing more costs and at the same time, keeping the allocated SWs for lower value of failure rate of SWs.
2) Increasing the RDG capacity enhanced the reliability cost of the system and led to decreasing the number of SWs allocated at the same time since it deteriorates the reliability and the total cost of the system as well.
3) Past a certain value of failure rate, the number of SWs allocated drops to thwart worsening the reliability since the effect of switches on reliability deterioration dominates the contribution of SWs to reliability enhancement.
4) The Monte Carlo simulation indicated that a similar output for results and the slight discrepancy (XX percent) is due to the higher accuracy of Markov-natured proposed model that considers the simultaneous fault occurrence.

5) The failure rate of SWs significantly affects the planning of the system and as the failure rates, the corresponding costs increase too. While SW is generally used to enhance the reliability of the system. Accordingly, ignoring the failure of SWs results in the overestimation of their contribution to the reliability enhancement of the system which makes it vital to consider the failure rate of SWs in the model.

The future work can consider applying different optimization algorithms to work on enhancing the accuracy of the output which was not the main purpose of the current paper. In addition, other types of the DG technologies can be studied to caption different aspects of the planning.

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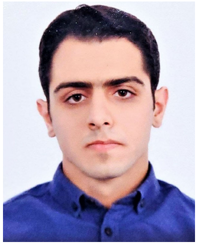

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