Risk-based Switch Placement in Electric Distribution Network in Presence of Performance Based Regulation

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Abstract: A reward and penalty scheme (RPS) is used for setting up the service quality which exposes the distribution companies to financial benefits caused by demand for the reliability of customers. In this paper, an algorithm for the optimal switch number and placement in distribution networks in the presence of RPS is presented. The primary objective is reliability improvement and minimization of the cost of sectionalizing switches (SS) and tie switches (TS) for a given regulatory period considering acceptable financial risk. In this algorithm, the uncertainty in the reliability appears as financial risk. A genetic algorithm is adopted to solve the optimization problem. The number and location of SS and TS are found while financial incentives of RPS, capital investment and annual operation and maintenance costs are considered. The performance of the proposed approach is assessed and illustrated on a real distribution network. The results show the efficiency of the proposed algorithm.

Keywords: Distribution networks regulation, performance based regulation, power system reliability, reward and penalty scheme, switch placement.
Nomenclature

$CC_{i}^{SS}$ Capital investment and installation cost of SS installed in year $t$.

$CC_{i}^{TS}$ Capital investment and installation cost of TS installed in year $t$.

$CC_{i}$ Energy price ($/kWh$) for load sector $l$.

$D_{s,z,k}$ Average duration of unplanned outage interruption $z$-th zone of $s$-th feeder result of failure occurrence in $k$-th zone of $s$-th feeder.

$DR$ Annual discount rate.

$f_{i}(SAIDI)$ Probability distribution of SAIDI for plan $i$.

$f(CENS_{t})$ Probability distribution of energy not supplied cost in year $t$.

$f(N_{t,s,z})$ Frequency distribution of failures of $z$-th zone of $s$-th feeder in year $t$.

$MC_{t}^{SS}$ Operation and maintenance cost of SS in year $t$.

$MC_{t}^{TS}$ Operation and maintenance cost of TS in year $t$.

$m$ Life period of SS and TS.

$NC_{T}$ Total number of customers.

$NC_{s,z}$ Number of customers located in $z$-th zone on $s$-th feeder.

$P_{NS,s,z}$ Expected interrupted load (kW) in $z$-th zone of $s$-th feeder.

$RPI_{i}$ Probability distribution of reward penalty incentive for plan $i$.

RPS($SAIDI$) Reward penalty scheme based on SAIDI index.

$SC_{i}$ Switch placement cost for plan $i$.

$T$ Period of regulation.

$VaR_{\alpha}$ Value at risk at a given confidence level $(1 - \alpha)\%$.

$Z_{i}$ Financial outcome of plan $i$. 
\( Z_s \)  
Number of zones in s-th feeder.

\( \alpha_{l,s,z} \)  
Contribution percentage of load sector \( l \) in zone \( z \) of feeder \( s \).

\( \eta_i \)  
Expected profit of plan \( i \).

\( \chi_i \)  
Risk of plan \( i \).

\( K, I \)  
Number of SS’s and TS’s downstream of faulty zone, respectively.

1. Introduction

In recent years, regulators have tried to create a competitive condition and grant the electricity distribution companies to the private sectors [1]. The natural monopoly transmission and distribution activities are subjected to economic regulation. The aim of regulation in restructured distribution networks is to improve the economic efficiency, the quality of their services and protection of the customers against unreasonable tariffs on the services. Performance based regulation (PBR), on one hand, encourages cost efficiency and, on another, suffers from lack of encouragement for quality of service. Under this regulation, customers will receive services with lower quality than their desirable level. Due to this weakness in PBR, RPS is proposed in order to guarantee the reliability of the distribution companies. These incentives modify the company’s revenues according to their performance and penalize companies with lower quality levels and reward companies with high quality levels [2]. In the presence of RPS, DSOs should make decisions regarding whether to design the distribution network in order to improve or maintain the reliability of service [3]. Due to economic competition and deregulation, the risk of power outages is increased [4]. An effective way to improve reliability is to use TS and SS. Both the number and location of TS and SS need to be optimized [5]. Many mathematical methods and intelligent algorithms, including,
simulated annealing [6], genetic algorithms [7-10], particle swarm optimization (PSO) [11-13], ant colony search algorithm [14, 15], immune algorithm [16] have been proposed for optimal switch placement. In [11], a novel three-state approach based on PSO was developed for determining the optimal number and locations of two types of switches in distribution systems. Multiobjective switch placement (MOSP) algorithm based on PSO was proposed in [12] to solve the optimization of the sectionalizing switch placement problem in distribution networks. The proposed algorithm presents a set of solutions instead of a unique solution. A multiobjective planning scheme for the allocation of sectionalizing switches and tie lines using PSO has been investigated in [13]. In [17], a mixed integer programming for sectionalizing switches placement by integrate Switch malfunction probability was proposed. In [18], a new technique based on three operations was presented to solve the reconfiguration problem of distribution systems. A non-dominated sorting genetic algorithm II for determining the number and location of remote controlled switches was presented in [19]. In this paper, the risk awareness of distribution companies is scrutinized through conditional value at risk. In [20], a mixed integer linear programming (MILP) approach was proposed for determining the optimal number, type and location of the new automation devices and the new locations of the existing devices. A method based on micro-genetic algorithm (MGA) and fuzzy logic (FL) for sectionalizing switch placement was proposed in [21]. In [22], a formulation was proposed for an optimal placement of switches and reclosers in a distribution system under uncertainties in load data, system failure and repair rates. In [5], a MILP approach is used to solve the sectionalizing switch placement in the presence of DG. A method based on harmony search (HS) algorithm for optimal allocation of DG and recloser has been suggested in [23]. In [24], simple and effective model of the optimization problem was proposed to provide the optimal number, type, and position of the switches that must be installed each year to achieve both the targeted
annual reliability improvement and the cheapest investment cost during the overall regulatory period. DSOs can choose the target level that it would like to reach each year of the regulatory period and then to know the related overall minimum investment cost that it has to pay for that target level. Due to introduction of RPS in distribution network, the importance of reliability has extremely increased for DSOs. In [24], the reliability of each year for a given regulatory period is considered as the objective function, however, the RPS cost is not calculated.

In the presented algorithm in this paper, RPS cost in the regulatory period will be added to capital investment, and annual operation and maintenance costs of switches and the number and location of the switches is annually obtained in the regulatory period. In this algorithm, the uncertainty in the reliability is appeared as financial risk. In fact, the main contribution of this paper is based on suggesting a risk-based switch placement in regulated distribution networks considering acceptable financial risk. This paper covers two topics in relation to previous research. First switch placement problem is adopted with RPS scheme and second the risk based formulation is incorporated to handle the uncertainty that DSO faced by.

The steps of the proposed risk-based switch placement model are shown in Fig. 1, and discussed in this section. In the first step, the risk-based objective function is defined. In order to calculate the financial risk of placement of switches, i.e. the probability distribution (PD) of financial outcome from installing switch, it is required to calculate the uncertainty of system reliability, which is usually, expressed using the PD of SAIDI. For that, this paper introduces an algorithm to determine the PD of outage frequency in step 2.a, and extracts the PD of SAIDI from the PD of outage frequency by applying restoration algorithm in step 2.b and 2.c. Having the PD of SAIDI, the PD of financial outcome is calculated in step 2.d. and step 3 finds the optimal solution, i.e. the best switch placement plan, using genetic algorithm.
This paper is organized as follows. The definition of RPS is explained in Section 2. Section 3 presents the problem formulation. Obtained results are presented in Section 4. Section 5 provides the main conclusions.

2. Reward and Penalty Scheme

The reward-penalty schemes do not have fixed structure in all conditions and could be modified according to requirements [3]. In general form, RPS comprises three zones: the dead zone in which the company does not receive reward or penalty, the reward zone in which the company is rewarded for quality improvement and the penalty zone in which the company is penalized for quality deterioration. Reliability indices are usually based on average customer interruption indices such as SAIFI (System Average Interruption Frequency Index) and SAIDI (System Average Interruption Duration Index) [25]. In this paper, we use SAIDI as a reliability index. If more than one reliability index should be included, a weighted RPS approach could be applied. In the weighted RPS approach, the RPS cost associated with each index is weighted based on the customer concern [2]. Fig. 2 shows the general form of the RPS [21].

3. Problem Formulation

The TS and SS are installed in order to increase the reliability in distribution networks. They are commonly used to improve reliability, isolate a fault, reconfigure, and restore the network, and hence, reduce the interruption cost after a fault [14]. An appropriate allocation of switching devices is a key factor for reducing the restoration time and improving reliability index. Reliability performance is usually based on average customer interruption indices such as SAIFI and SAIDI, and EENS (expected energy not supplied). In this paper, we use SAIDI and EENS as a reliability indices. Fig.3 shows the flowchart of the proposed algorithm.
3.1. Risk-based objective function formulation

In stochastic optimization problems, the profit is a random variable usually expressed as a probability distribution form. In an optimization problem, a function is needed which specifies the probability distribution of this random variable. In this paper, the expected value of the profit is used for this purpose. Even though the expected value has numerous advantages for describing the random variable, unfortunately it cannot specify other characteristics of the distribution associated with the random variable. For example, it is very important for decision makers that, in addition to the expected amount of the acceptable profit, the risk of encountering a negative profit or loss be shown by the random variable. Therefore, in order to control the risk of experiencing losses, it is necessary to consider a term measuring the risk associated with a profit distribution. In this paper, the conditional value-at-risk \((CVaR)\) index is used.

3.1.1 Risk Measure: The Value at Risk \((VaR)\) index is usually used to estimate the risk. This index measures the worst expected loss at a given confidence level \((1-\alpha)\%\). This index is expressed with the following equation:

\[
P[Z_i \leq VaR_{\alpha}] = \alpha
\]  

(1)

The \(VaR\) index does not provide information about the worst potential losses which are beyond the confidence level. Therefore, in this paper, \(CVaR\) is used which is defined as the expected loss exceeding \(VaR\). \(CVaR\) of plan \(i\) is expressed as below:

\[
CVaR_i = E[Z_i | Z_i < VaR_{\alpha}] = \frac{\int_{VaR_{\alpha}}^{\infty} Z_i f(Z_i) dZ_i}{P[Z_i < VaR_{\alpha}]} 
\]  

(2)

3.1.2 Objective function: The objective function for risk-based switch placement study would be:

\[
\max \{(1 - \beta) \times \eta_i - \beta \times \chi_i \}
\]  

(3)
The $\eta_i$ and $\chi_i$ are formulated as follows:

$$\eta_i = E[Z_{ij}]$$  \hspace{1cm} (4) \\
$$\chi_i = CVaR_i$$  \hspace{1cm} (5)

The factor $\beta \in [0,1]$ is used to model the risk aversion tendency of DSO in the objective function. The value of zero for $\beta$ shows that DSO is risk neutral and the value of one for this factor implies that the DSO is risk averse.

3.1.3 Constraint

The function problem should meet technical constraints. Technical constraints are power demand and supply balance, maximum allowable voltage drops at load points, network radiality, and maximum feeder current limits.

3.2 Probability distribution of financial profit: The probability distribution of financial profit from installing SS and TS for plan $i$ is given by:

$$Z_{ij} = (RPI_i - SC_i)$$  \hspace{1cm} (6)

The $RPI_i$ is defined by:

$$RPI_i = RPS(SAIDI_i) f_i (SAIDI)$$  \hspace{1cm} (7)

Which implies the reward/penalty incentive obtained from plan $i$.

The switch placement cost ($SC_i$) of plan $i$ is mathematically expressed as follows:

$$SC_i = \sum_{t=1}^{T} \left[ (CC_{i}^{SS} + CC_{i}^{TS}) \left( \frac{DR(1 + DR)^{m}}{DR(1 + DR)^{m} - 1} \right) (1 + DR)^{-(t-1)} \right] + \sum_{t=1}^{T} \left[ (MC_{i}^{SS} + MC_{i}^{TS} + f(CENS_{i}) ) (1 + DR)^{-t} \right]$$  \hspace{1cm} (8)

3.3. Determining the probability distribution of system reliability
In order to evaluate the reliability of each plan, the following algorithm is used:

Step 1: the suggested switches in the first year of each plan gets applied on the network and then the network is zoned so that every section placed between two separating switches will form a zone.

Step 2: calculating the distribution of outage frequencies during the first year with respect to the failure rate of each zone.

Step 3: performing load restoration algorithm with assumption of fault occurring in each zone and calculating the interruption duration in all of the zones.

Step 4: calculating the reliability indexes (ENS and SAIDI).

The uncertainty of the SAIDI index is caused by the uncertainty of outage duration and outage frequency. The outage duration is related to the location of the fault and the restoration time which are assumed to be deterministic in this study and only the uncertainty caused by outage frequency has been taken into consideration herein.

Probability distribution of SAIDI is expressed as below:

$$f(SAIDI) = \frac{1}{NC_T} \sum_{t=1}^{T} \sum_{s=1}^{S} \sum_{z=1}^{Z_s} \left\{ f(N_{t,s,z}) \sum_{k=1}^{Z_s} \left[ D_{s,z,k} \cdot NC_{s,z} \right] \right\} \quad \text{(9)}$$

$$f(CENS_t)$$ is calculated based on the uncertainty of the ENS index as follows:

$$f(CENS_t) = \sum_{s=1}^{S} \sum_{z=1}^{Z_s} \left\{ f(N_{t,s,z}) \sum_{k=1}^{Z_s} P_{NS,s,z} \sum_{l=1}^{4} \left[ \alpha_{l,s,z} D_{s,z,k} \cdot C_l \right] \right\} \quad \text{(10)}$$

As shown in (9) and (10), it is necessary to calculate $$f(N_{t,s,z})$$ to obtain both $$f(SAIDI)$$ and $$f(CENS_t)$$. Therefore, an algorithm is proposed for extracting $$f(N_{t,s,z})$$ using the random generation method of failure times whose flowchart is shown in Fig. 4.
Assuming a constant failure rate for section \( z \) of feeder \( s \), this algorithm produces the number of failures of the intended section in the \([0, T]\) interval. Producing a random number \( u \) and placing it in Equation 11, the time of failure occurrence will be achieved:

\[
T_{\text{new}} = -\ln(u) / \lambda_{s,z}
\]  

(11)

The times of the following failures will be determined in a similar way and the algorithm goes on until the time of the last failure achieved occurs after time \( T \). Then, the failures occurred in the \([0, T]\) interval will be counted. If this algorithm is repeated enough, the frequency distribution of the desired zone will be achieved.

4.3.1. Restoration method: When a fault occurs in a given zone of network, the outage time of customers is obtained as follows [3]:

a. Customers located downstream the faulty zone: their outage time and the repair time are equal if no tie switches and back up services exist. However if they exist, the outage time is equal to the time required for switching.

b. Customers located upstream the faulty zone: the outage time of these customers and switching time are equal.

c. Customers located in the faulty zone: the outage time of these customers and repair time are equal.

In order to determining above mentioned outage times, a restoration algorithm proposed based fundamental cut-set concept in graph theory.

**Finding fundamental cut set of downstream of faulty zone:** Distribution network can be considered as a rooted spanning tree \( T \) of a graph \( G = (V, E) \). The \( T \) can be changed to another tree by opening a line \( e \) of \( T \) and closing a non-tree line \( m \in E - T \) if \( m \) is a fundamental cut-set of \( e \). Similarly a distribution network can be restored by opening downstream \( SS \) of faulted zone and closing \( TS \) if \( TS \) is a fundamental cut-set of \( SS \). By identifying the fundamental cut-set, creating of
unfeasible configurations can be avoided during restoration process. To finding fundamental cut-set of node \( v \), all node of distribution network must be numbered in the preorder method [26]. So \( \text{pre}(v) \) denotes the preorder number of node \( v \) and \( \text{dows}(v) \) presents the number of downstream nodes of \( v \). Also the \( a(v) \) is used to denote the quantity \( \text{pre}(v) + \text{dows}(v) \) [27]. As preorder numbering defined, any downstream node \( w \) of \( v \) have a preorder number greater than \( \text{pre}(v) \) but not more than \( a(v) \) or can be written:

\[
\text{pre}(v) < \text{pre}(w) \leq \text{pre}(v) + \text{dows}(v) \quad (12)
\]

And any non-downstream node of \( v \) either have a preorder number which either less than \( \text{pre}(v) \) or greater than \( a(v) \). The fundamental cut-sets of \( v \) can be defined as set of \( E_1(v) \cup E_2(v) \) which is defined as follows:

\[
E_1(v) = \left\{(b,c): 1 \leq \text{pre}(b) < \text{pre}(v) \text{ and } (b,c) \in E - T \right\} \quad (13)
\]

\[
E_2(v) = \left\{(b,c): \text{pre}(v) \leq \text{pre}(b) \leq a(v) \text{ and } (b,c) \in E - T \right\} \quad (14)
\]

**Restoration algorithm:** After assuming fault on zone \( z \) in feeder \( s \), the following steps are used for restoration process:

1. **Step 1:** isolation process is carried out by opening upstream and downstream switches closest to faulty section.
2. **Step 2:** find upstream zones, faulty zone and downstream zones of fault section. The loads of upstream zones are restored after switching time and interruption duration of load of faulty zone are equal to repairing time.
Step 3: for any zone at downstream of faulty zone, find all fundamental cut-sets (TS) of its root node and sort them based on their available transfer capability \{TS1,...,TSi\};

Step 4: open all SS’s of the downstream of faulty zone and set i=1;

Step 5: set k=1; close TSi \(\forall i = 1,2,...,I\) and sort all open switches SSk \(\forall k = 1,2,...,K\) based on their adjacency to TSi; then check violation from the constraint by load flow analysis;

Step 6: if violation occurred, set i=i+1 and go to step 5.

Step 7: else close the adjacent SSk \(\forall k = 1,2,...,K\) and check violation from constraint by load flow analysis;

Step 8: if violation occurred, store switch operation set \{open SSk, close TSi \} and assign the zones in the pass between TSi and SSk as restored zone else set k=k+1 and go to step 7;

Step 9: if all downstream zones restored, store switch operation \{close TSi \} and go to 12.

Step 10: else if k <K and i <I, update K based on number of remaining SS’s of the downstream of faulty zone; set i=i+1 and go to step 5.

Step 11: specify the switch operation pairs, restored and unrestored zones.

Step 12: calculate restoration time for restored zones.

The restoration algorithm flowchart is shown in Fig. 5.

3.4. Finding optimal solution using genetic algorithm

In this paper, genetic algorithm is presented for optimal number, type, and position of the switches in regulated distribution network. A chromosome specified by \(N \times 2\) matrix witch N is number of candid locations of SS and TS. Each row show binary
number which its equivalent decimal number indicates years of installation as shown in Fig. 6.

4. Numerical result

The proposed method has been tested on real 172-buses power distribution system of Ilam Power Distribution Company (IPDC). This network consisting of 7 feeders and 3 tie switches, as shown in Fig. 7. In this network, 25 candidate locations for installing the sectionalizing switches and 6 candidate locations for installing the tie switches are suggested and shown on Table 1. The investment cost of sectionalizing switches is $4700 and the cost of line is assumed to be 7000 $/km. The annual maintenance cost is 2% of the investment cost, the life period of the switches is 15 years, the load growth rate is 3% and the interest rate is 8% [28]. The price of undelivered energy during outages is shown in Table 2 and RPS parameters are given in Table 3. The regulatory period is three years. For GA application, the parameters were selected as shown in Table 4. In this paper, MATLAB coding is developed to validate the proposed algorithm.

The algorithm presented in this paper is investigated in four different case studies:

Case 1 (Base Case): current distribution network (before installing any switches in the system);

Case 2: optimal sectionalizing switch placement by applying the proposed algorithm;

Case 3: optimal sectionalizing switch placement regardless of RPS cost;

Case 4: optimal sectionalizing switch placement considering the budget limitations.

In Case 1 (Base Case), two switches are located at locations 43 and 156. If there is no investment put on installation of the other switch, the results of simulation shows
that at the end of the third year, the profit of the company and the losses beyond VaR expectation are respectively -$56771 and $97948. Also, the expected value of SAIDI index in this network is equal to 401.4 minutes.

Table 5 shows the results of optimal sectionalizing switches and tie switches in Case 2 using the proposed algorithm. The results show that if the company is risk neutral ($\beta = 0$), using 11 sectionalizing switches and 2 tie switches can have a profit equal to -$6080 at the end of the third year which will have been improved about $50691 compared to the Base Case. The optimum number of the switches for each year and their locations are given in Table 5. In this case, the risk index (CVaR or expected shortfall) is $24715. This means the expected loss at a confidence level equal to 95% is $24715 which has a reduction of $73233 in comparison with the Base Case. The expected value of SAIDI index in this case is reduced by 43.3% compared to the Base Case, and it has reached to 227.5 minutes.

As the switch placement results show, if the company is risk neutral, with installing fewer switches (11 sectionalizing switches and 2 tie switches), it can have a higher expected profit. On the other hand, there is the risk of a probable higher loss. As the company grows in being risk averse, the number of the installed switch increase. For instance, if $0.1 \leq \beta \leq 0.2$, according to Table 5, the optimal number of switches is 12 sectionalizing switches and 2 tie switches. If the company is completely risk averse ($\beta = 1$), then the investment must be increased and 13 sectionalizing switches and 2 tie switches must be installed. In this case, the risk index and the expected profit of the company have respectively decreased to $19549 and -$6794. The increase of switch installation will lead to reduction in the expected profit of the company. The location of the sectionalizing switches in different scenarios will be different but in all of the scenarios there are only two tie switches which are for the two feeders which did not have any tie switches.
Table 6 shows the results of optimal sectionalizing switches without considering the RPS cost in the regulatory period. The results of the simulation indicate that in this case the number of the optimum switches will be decreased in comparison with the case 2. In this case, if the company is risk neutral, the optimum number of the sectionalizing switches will be 5, the optimum number of the tie switches is 1, the risk index is $58332 and the expected profit of the company is -$47085. The expected value of SAIDI in this case is 17.1% decreased in comparison with the Base Case and is increased by 46.2% in comparison with the Case 2. The results show that by considering RPS, the company will find a financial incentive for improving the reliability. In Case 2, the company will receive $47162 for RPS which covers the switch placement cost. Comparing the results of Table 5 with those of Table 6 indicate the role of RPS in motivating the improvement of the reliability.

The results of Table 5 show that due to the lack of budget limitations, the installation of the switches are mostly offered in the first year. In the case 4, the investment limitation is assumed to be $30000. The results of this simulation are given in Table 7. The results of Table 7 show that if a company is risk neutral, the optimum number of the sectionalizing switches is 13, the optimum number of the tie switches is 2, the risk index is $40540 and the expected profit of the company is -$9162. In this case, due to the limitation of the investment, the number of the considered switches are increased in the second and third years. The expected value of SAIDI in this case has increased 8.5% compared to the case 2.

The collection of optimal solutions for case 2, in terms of expected profit and risk, defines an efficient frontier (Fig. 8). The efficient frontiers are appropriate tools used by decision makers to evaluate the trade off between expected profit and risk. It can be seen that a small value of $\beta$ yields a plan with high expected profit and also high risk. Besides, a large value of $\beta$ attains a plan with smaller expected profit and smaller risk.
In this paper, four crossover and mutation strategies which are used in the different literatures are tested. The results of the optimization of each mutation strategy have been compared and the best answer is chosen. Due to lack of space, we cannot insert all tables in this paper. Moreover, we chose the optimal answer during the 30 trial runs and each run consist of 200 iterations. To demonstrate the superiority of the proposed algorithm, the results obtained from GA are compared with well-established PSO algorithm. Table 8 shows the results of optimal sectionalizing switches and tie switches in Case 2 using the PSO algorithm. The results show that the GA presents the better results for $\beta=0$ and $0.3 \leq \beta \leq 1$.

5. conclusion

In the presence of PBR, the distribution companies must set up the reliability enhancement programs so that they do not face penalties at the end of the period and use bonus benefits as much as they can. In this paper, a risk-based method is proposed for sectionalizing switches and tie switches in the presence of RPS. Herein, the aim is to optimize the reliability level and minimize the costs which have been achieved by genetic algorithm. The suggested algorithm is capable of obtaining the optimum number and location of both sectionalizing switches and tie switches in the regulatory period by choosing a proper risk level. The used risk index in this paper is CVaR which is an indicator of the expected loss value being more than the value at risk. The proposed method is applied to a real distribution network and its results are given for a three years’ regulatory period. In this paper, the impacts of RPS cost in the regulatory period on the optimum number and location of the switches and the network reliability are shown. In case the company does not have any annual budget limitations, it can choose optimal sectionalizing switch placement considering any desired risk level. The results show that if the company is risk averse, it is needed to install more switches and therefore the
expected profit of the company will be decreased. However, if more profit is desired, the switch installation may have a lower cost while a higher risk will be inevitable.

6. References


**Biographies**

**Mohsen Simab** received the BSc degree in Electrical Engineering from Amir Kabir University, Tehran, Iran, and the MSc and PhD degrees from Tarbiat Modares University, Tehran, Iran, in 2003, 2005, and 2011, respectively. He is an Assistant Professor in power systems at the Department of Electrical Engineering, Marvdasht Branch, Islamic Azad University, Marvdasht, Iran. His main research interests are electric distribution regulation, power system operation, and power system reliability.

**Amin Moradkhani** was born in Abdanan, Iran, in 1981. He received the BSc degree in electrical engineering from the University of Amir Kabir, Tehran, Iran, in 2004, and the MSc and PhD degrees in electrical engineering from the Tarbiat Modares University, Tehran, Iran, in 2006 and 2014, respectively. In 2014, he joined the Department of Electrical Engineering, University of Ilam, as an Assistant Professor. His current research interests include planning and operation of power distribution system, reliability, smart grid.
Table Captions:

Table 1 Candid location of TS
Table 2 The value of energy of different customer type
Table 3 Input value of RPS parameters for SAIDI index
Table 4 Genetic algorithm parameters
Table 5 Optimal sectionalizing switch placement by applying the proposed algorithm
Table 6 Optimal sectionalizing switch placement regardless of RPS cost
Table 7 Optimal sectionalizing switch placement considering the budget limitations
Table 8 Optimal sectionalizing switch placement by applying the PSO algorithm

Figure Captions:

Fig. 1. The steps of risk-based switch placement
Fig. 2. A general RPS.
Fig. 3. Flowchart of the proposed SS and TS placement.
Fig. 4. Flowchart of the algorithm for determining of outages frequency distribution.
Fig. 5. Flowchart of the restoration algorithm.
Fig. 6. Chromosome structure.
Fig. 7. Single line diagram of real 172-buses power distribution system.
Fig. 8. Efficient frontier of DSO in switch placement
### Table 2 Candid location of TS

<table>
<thead>
<tr>
<th>TS candid</th>
<th>From bus</th>
<th>To bus</th>
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</thead>
<tbody>
<tr>
<td>T1</td>
<td>133</td>
<td>152</td>
</tr>
<tr>
<td>T2</td>
<td>17</td>
<td>40</td>
</tr>
<tr>
<td>T3</td>
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<td>68</td>
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<tr>
<td>T6</td>
<td>52</td>
<td>120</td>
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</table>

### Table 2 The value of energy of different customer type

<table>
<thead>
<tr>
<th>Category</th>
<th>Value of energy ($/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>0.05</td>
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<tr>
<td>Commercial</td>
<td>0.2</td>
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<tr>
<td>Industrial</td>
<td>0.2</td>
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<tr>
<td>Institution</td>
<td>0.14</td>
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### Table 3 Input value of RPS parameters for SAIDI index

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<th>RCP</th>
<th>RP</th>
<th>PP</th>
<th>PCP</th>
<th>Incentive rate (1000$/min)</th>
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<tbody>
<tr>
<td>227</td>
<td>315</td>
<td>473</td>
<td>553</td>
<td>0.375</td>
</tr>
</tbody>
</table>

### Table 4 Genetic algorithm parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of iteration</td>
<td>200</td>
</tr>
<tr>
<td>Population size</td>
<td>40</td>
</tr>
<tr>
<td>Mutation probability</td>
<td>0.02</td>
</tr>
<tr>
<td>Crossover probability</td>
<td>0.8</td>
</tr>
<tr>
<td>Chromosome length</td>
<td>31×2 binary genes</td>
</tr>
</tbody>
</table>

### Table 5 Optimal sectionalizing switch placement by applying the proposed algorithm

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>Year</th>
<th>New switches locations</th>
<th>$\eta_i$ ($)</th>
<th>$\chi_i$ ($)</th>
<th>$SC$ ($)</th>
<th>RPI ($)</th>
<th>E(SAIDI) (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>S3, S5, S10, S16, S17, S20, S25, T2, T4</td>
<td>-6080</td>
<td>24715</td>
<td>53242</td>
<td>47162</td>
<td>227.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>S11, S13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>S14, S19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1 ≤ $\beta$ ≤ 0.2</td>
<td>1</td>
<td>S3, S5, S10, S11, S13, S14, S20, S25, T2, T4</td>
<td>-6387</td>
<td>20931</td>
<td>54643</td>
<td>48256</td>
<td>221.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>S17, S19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>S6, S8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3 ≤ $\beta$ ≤ 1</td>
<td>1</td>
<td>S2, S6, S10, S11, S13, S16, S19, S20, S25, T2, T4</td>
<td>-6794</td>
<td>19549</td>
<td>55339</td>
<td>48544</td>
<td>213.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>S5, S17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>S3, S14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 6 Optimal sectionalizing switch placement regardless of RPS cost
<table>
<thead>
<tr>
<th>$\beta$</th>
<th>Year</th>
<th>New switches locations</th>
<th>$\eta_i$ ($)</th>
<th>$\chi_i$ ($)</th>
<th>$SC$ ($)</th>
<th>RPI ($)</th>
<th>$E$(SAIDI) (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 \leq \beta \leq 0.1$</td>
<td>1</td>
<td>S5, S11, S25</td>
<td>-58332</td>
<td>47085</td>
<td>0</td>
<td>332.6</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>S13</td>
<td>-47085</td>
<td>58332</td>
<td>47085</td>
<td>0</td>
<td>332.6</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>S3, T2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0.2 \leq \beta \leq 1$</td>
<td>1</td>
<td>S5, S25</td>
<td>-57976</td>
<td>47494</td>
<td>0</td>
<td>334.5</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>S11</td>
<td>-47494</td>
<td>57976</td>
<td>47494</td>
<td>0</td>
<td>334.5</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>S13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 7** Optimal sectionalizing switch placement considering the budget limitations

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>Year</th>
<th>New switches locations</th>
<th>$\eta_i$ ($)</th>
<th>$\chi_i$ ($)</th>
<th>$SC$ ($)</th>
<th>RPI ($)</th>
<th>$E$(SAIDI) (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 \leq \beta \leq 0.1$</td>
<td>1</td>
<td>S5, S11, S13, S16, S20, S25</td>
<td>-9162</td>
<td>40540</td>
<td>43740</td>
<td>246.8</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>S2, S19, T2, T4</td>
<td>-9162</td>
<td>40540</td>
<td>43740</td>
<td>246.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>S6, S10, S14, S17, S24</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0.2 \leq \beta \leq 1$</td>
<td>1</td>
<td>S2, S5, S13, S25, T2</td>
<td>-9372</td>
<td>38728</td>
<td>43707</td>
<td>249.6</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>S11, S16, S19, S20, T4</td>
<td>-9372</td>
<td>38728</td>
<td>43707</td>
<td>249.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>S6, S8, S10, S15, S17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 8** Optimal sectionalizing switch placement by applying the PSO algorithm

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>Year</th>
<th>New switches locations</th>
<th>$\eta_i$ ($)</th>
<th>$\chi_i$ ($)</th>
<th>$SC$ ($)</th>
<th>RPI ($)</th>
<th>$E$(SAIDI) (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta = 0$</td>
<td>1</td>
<td>S3, S6, S10, S16, S17, S20, S25, T2, T4</td>
<td>-6157</td>
<td>24604</td>
<td>53393</td>
<td>47236</td>
<td>227.9</td>
</tr>
<tr>
<td>2</td>
<td>S11, S13</td>
<td>-6157</td>
<td>24604</td>
<td>53393</td>
<td>47236</td>
<td>227.9</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>S6, S15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0.1 \leq \beta \leq 0.2$</td>
<td>1</td>
<td>S3, S5, S10, S11, S13, S14, S20, S25, T2, T4</td>
<td>-6387</td>
<td>20931</td>
<td>54643</td>
<td>48256</td>
<td>221.3</td>
</tr>
<tr>
<td>2</td>
<td>S17, S19</td>
<td>-6387</td>
<td>20931</td>
<td>54643</td>
<td>48256</td>
<td>221.3</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>S6, S8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0.3 \leq \beta \leq 1$</td>
<td>1</td>
<td>S2, S5, S10, S11, S14, S16, S19, S20, S25, T2, T4</td>
<td>-6811</td>
<td>19755</td>
<td>55431</td>
<td>48620</td>
<td>215.4</td>
</tr>
<tr>
<td>2</td>
<td>S6, S17</td>
<td>-6811</td>
<td>19755</td>
<td>55431</td>
<td>48620</td>
<td>215.4</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>S3, S13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
1. Define risk-based objective function formulation
   - Define Risk measure
   - Define objective function
   - Define PD of financial profit

2. Determining the PD of system reliability
   2.a Determining the PD of outage frequency
   2.b Define restoration method
   2.c Extracting the PD of SAIDI from PD of outage frequency
   2.d Calculating the PD of financial outcome using PD of SAIDI

3. Optimize switch placement problem

**Fig. 1. The steps of risk-based switch placement**

**Fig. 2. A general RPS.**
Fig. 3. Flowchart of the proposed SS and TS placement.
Set \( T^* = 0 \), \( n = 0 \)

Generate \( u \sim U(0,1) \)

\( T_{\text{new}} \leftarrow -\ln(u)/\lambda_{s,z} \)

If \((T_{\text{new}} > T)\)

\( T^* \leftarrow T_{\text{new}} \)
\( T_i \leftarrow T_{\text{new}} \)
\( n \leftarrow n+1 \)

Yes

\( N_{t,s,z}(j) = n-1 \)

Extracting frequency distribution \( f(N_{t,s,z}) \)

If \((j < J)\)

\( j = j+1 \)

Yes

NO

Input \( \lambda_{s,z} \)
Set \( j = 1 \)

Fig. 4. Flowchart of the algorithm for determining of outages frequency distribution.
start
Set fault section x

- Find upstream zones
- Find fault zone
- Find downstream zones

Find all fundamental cut-set of dy and sort them based on max of ATC: \( \{TS_1, ..., TSI\} \)

\[ i=1, \ k=1 \]
Open all switch in downstream of faulty zone \( \{SW_1, ..., SW_K\} \)

Close \( TSi \) and run load flow

\[ i=i+1 \]

Check violation from constraint

Update K based on remaining SS’s and set \( k=1 \)

Close next adjacent switch of \( \{SW_1, ..., SW_K\} \)
And run load flow analysis

\[ k=K \]

no

\[ k=k+1 \]

yes

Check violation from constraint

Remember switch operation set:
Open:SW\( k \), Close:T\( Si \)
Restored nodes between T\( Si \), SW

\[ i=i+1 \]

yes

no

\[ i \leq I \]

no

Show switch operation pairs
Show restored nodes
Show unrestored nodes

end

Fig. 5. Flowchart of the restoration algorithm.
The rows show the candidate location of SS or TS switches. Binary code indicates years of installation:

- 0 0: No switch
- 1 0: Switch installed at first year
- 0 1: Switch installed at second year
- 1 1: Switch installed at third year

**Fig. 6. Chromosome structure.**

**Fig. 7. Single line diagram of real 172-buses power distribution system.**

**Fig. 8. Efficient frontier of DSO in switch placement.**