Electronics and Electrical Engineering

AIMS Electronics and Electrical Engineering, 6(3): 247–264.
DOI: 10.3934/electreng.2022015
Received: 14 December 2021
Revised: 08 June 2022
Accepted: 12 June 2022
Published: 29 July 2022

http://www.aimspress.com/journal/ElectrEng

Research article

Reliability enhancement of distribution networks with remote-controlled switches considering load growth under the effects of hidden failures and component aging

Umesh Agarwal[1,]*, Naveen Jain[1] and Manoj Kumawat[2]

[1] Department of Electrical Engineering, College of Technology and Engineering, Udaipur, Rajasthan, India
[2] Department of Electronics and Electrical Engineering, National Institute of Technology Delhi, Delhi, India

* **Correspondence:** Email: umeshbkb.agarwal@gmail.com; Tel: 9079900245; Fax: +912942471056.

Abstract: Over the last decade, automated distribution networks have grown in importance since traditional distribution networks are insufficiently intelligent to meet the growing need for reliable electricity supplies. Because the distribution network is the least reliable and the sole link between the utility and its customers, it is critical to improve its reliability. The remote-controlled switch (RCS) is a viable choice for boosting system reliability. It shortens the interruption period, which also minimizes the expected interruption cost and the amount of energy not served. Using the greedy search algorithm, this research expands the current reliability evaluation technique to include RCSs in distribution networks. The optimal location and numbers of RCSs have been evaluated with compromised cost. This study simultaneously takes into account the effects of load growth on system reliability indices, the impact of age on equipment failure rates and the hidden failure rate of fuses. The Roy Billinton test system's distribution network connected at bus 2 and bus 5 has been used to test the effectiveness of the suggested approach. The outcomes demonstrate that effective RCS deployment improves the radial distribution network's reliability indices significantly.

Keywords: aging; remote controlled switch; fuse failure probability; radial distribution network; RBTS; reliability

1. Introduction

In the present day, reliability evaluation of distribution networks is a topic of great concern. The requirement for continuous power supplies has continued to increases in competitive market scenarios with the reorganization of the network. In the report on Canadian customer service utility, 80% (approximately) of customer interruptions were due to the failure of any device in the distribution system [1,2]. Hence, enhancing the distribution network reliability in a cost-effective manner is the prime area of research for researchers.

The most significant attributes for the reliability analysis are failure frequency, restoration time and switching time. Among the several ways to achieve reliability enhancement, incorporation of the automatic switch can provide faster restoration of service during unexpected failure events and can thus improve the reliability. As depicted in [2], a fully automatic network will reduce the interruption cost by 80%; however, it is not economically justifiable to install the remote-controlled switch (RCS) at all of the customer points. The installation and maintenance cost for a large number of RCSs would be extremely high. Therefore, an optimal number of RCSs is to be determined to minimize the investment cost for maximization of the reduction in cost for energy not served (ENS). Hence, major research works in this area are briefed in this section.

Over the last few decades, the switch allocation issue has attracted researchers' attention and numerous studies have been conducted [3–5]. With new trends emerging in automation, RCSs are becoming increasingly important in reliability studies. In order to conduct the cost-worth assessments for reliability enhancement in distribution networks, the sequential Monte-Carlo simulation approach was used in [6]. This article show the calculations for various financial risk indices such as the volatility index, value at risk and conditional value at risk to quantify the risk. In [7], the malfunction probability of RCSs has been considered to extend the current reliability assessment procedure; the results showed that an RCS improves the system reliability. The non-dominated sorting genetics algorithm-II (NSGA-II) has been utilized in [8] for financial risk evaluation, as associated with RCS placement and tested on a 4-bus RBTS system.

Mixed integer programming has been used in [9,10] to find the optimal location and numbers of RCS in a distribution network for reliability enhancement. A new bi-directional model has been proposed in [11] for the optimal placement of switches and protective devices in a distribution network using genetics algorithm (GA) with distributed generation (DG). In [12], a fuzzy multi-criteria decision-making algorithm has been used to allocate the RCS in a distribution network. In [13], mixed integer non-linear programming has been used to identify the optimal location and numbers of protective devices, including the load uncertainties, temporary and permanent failure rates and repair rates. A bi-directional model has been proposed in [14] for the optimized allocation of reclosers in a distribution network using a GA approach. In [15], a GA-based method was used for simultaneous allocation of the DGs and RCSs in a distribution network for power loss reduction and reliability improvement. The problem of optimal allocation of RCSs in a distribution network has been resolved using a differential search (DS) algorithm in [16]. In [17,18], a memetic optimization approach has been utilized for the multi-objective planning of a distribution network with switches and protective devices, respectively. An analytical hierarchical process decision making algorithm has been implemented in [19] for the allocation of RCSs in a distribution network. In [20] for reliability enhancement, Esmaeilian and Fadaeinedjad implemented a binary gravitational search algorithm for the reorganization of the system and capacitor placement in a distribution system. A new sample construction with a path relinking method has been applied for the switch allocation in [21] to achieve the reliability enhancement of distribution networks. In [22], the reliability evaluation of a distribution network was performed in consideration of the aging effect of the components and load growth. In [23], the optimal location of fuse cutouts was determined in consideration of the fuse failure probability by using a Markov model.

Although an RCS can improve the system reliability in terms of service availability; however, it requires a huge investment as the installation cost of automatic switches is quite high. Therefore, considering the cost-effective allocation of RCSs in distribution network, this paper contributes the following to existing literature.

1) This paper identifies the optimal location of the RCS by applying a greedy search algorithm in distribution networks in a cost-effective manner.
2) It analyzes the impact of load growth on system and cost-worth reliability indices in the presence of RCSs.
3) It analyzes the impact of fuse failure probability in the presence of an RCS on the system and cost-worth reliability indices.
4) It analyzes the impact of feeder and transformer aging on the reliability parameters including RCS placement, for real-time analysis of the system.

The outcomes of the proposed research extend the present reliability evaluation procedure to include all possible system contingencies. The organization of the paper is as follows. Section 2 provides brief details about RCSs and the reliability indices for the system. Sections 3 and 4 are dedicated to problem formulation and mathematical modeling, respectively. Section 5 presents the strategy used for finding the optimal location and numbers of RCSs. Section 6 presents the computational results. Finally, Section 7 concludes the article.

2. Reliability indices and remote-controlled switch

In recent trends of the smart grid and modernization of existing distribution networks, the automatic switch is proved to be a source of revolution. It can improve the service availability at the consumer end as its switching time is very short. The RCS can be used as a sectionalizing switch (normally close) as well as tie switches (normally open). In a radial distribution network, normally closed automatic switches are used to isolate the faulty section from rest of the system. Therefore, the location of the automatic switch can improve the system reliability to a great extent.

The main contributing reliability indices are failure rate (λ), repair time (r), switching time (s) and annual outage duration (U). The failure rate represents the failure occurrence frequency. The repair time represents the time needed to repair the faulty section. The switching time represents the time required to restore the supply to a healthy section by switching off the faulty part. Outage duration is considered on an annual basis and calculated via either multiplication of the failure rate with repair time or multiplication of the failure rate and switching time.

Although the RCS does not have any considerable impact on the failure rate, the switching time, in the presence of an RCS is only 10 minutes; thus it will enhance the service availability by fast restoration of the supply. If a fault occurs downstream of the load point (LP) and no switch is available between them, then the LP will be affected by the repair time. In spite of this, if a normal switch is available between them, the switching time will be applicable. If the automatic switch is connected in place of a normal switch, the switching time would reduce by a great extent and fast service restoration could be achieved.

With the help of the failure rate, repair/switching time data and details about the load and customers at each load point, the cost-worth reliability indices “ENS and expected interruption cost (ECOST)” and System Reliability Indices “system average interruption frequency index (SAIFI) and system average interruption duration index (SAIDI)” can be evaluated. The ENS is the reliability indices that is the focus of this work.

If the failure rate is denoted as λ (failure/yr/km), the repair time as *r* (hours) and switching time as *s* (hours) then the annual outage duration *U* is given as

$$U_i = \sum_{i=1}^{n}(\lambda_i \times l_i) \times r_i + \sum_{i=1}^{n}(\lambda_i \times l_i) \times s_i \qquad (1)$$

where, l_i represents the feeder length.

The annual ENS is obtained as

$$ENS_i = \sum_{i=1}^{LP} U_i \times load_i \qquad (2)$$

Other reliability indices are represented in Table 1 below.

Table 1. System and cost-worth reliability indices.

S. No.	Reliability Indices	
1.	$SAIFI = \frac{\sum_{i=1}^{n} N_i * \lambda_i}{\sum_{i=1}^{n} N_t}$	(3)
2.	$SAIDI = \frac{\sum_{i=1}^{n} N_i * U_i}{\sum_{i=1}^{n} N_i}$	(4)
3.	$CAIDI = \frac{SAIDI}{SAIFI}$	(5)
4.	$ECOST = \sum_{i=1}^{n} \lambda_i * C_i * L_i$	(6)

In a distribution network, segments are branches of the network. In this structure, two branches may be connected through a switch in between them or they may be connected with an LP. An LP will experience an interruption under either of the following conditions:

- The segment connects the source and the LP.
- There is no fuse between the segment and the LP.

After occurrence of the failure, the time required to restore the service can be the restoration time or switching time. The condition illustrated in Figure 1 can be used to determine the service restoration time.

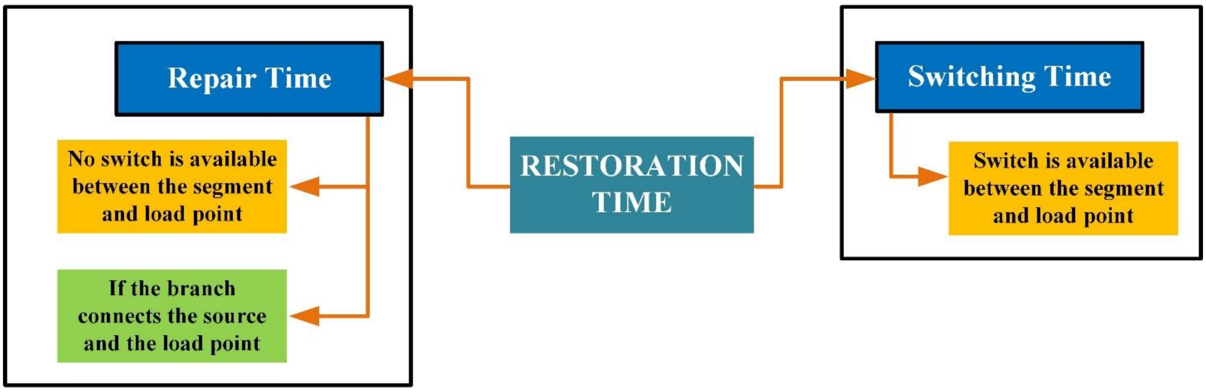

Figure 1. Conditions for service restoration.

The ENS depends on the load and annual outage duration. The annual outage duration depends on the failure frequency and restoration time or switching time. If the failure rate, length of sections, load at the LPs and switching time or repair time increases, then the ENS will also increase.

3. Problem statement

The prime objective of this work was to identify the optimal location and number of RCSs in a distribution network to reduce the ENS. With the increased quantity of RCSs, the ENS may get reduced, but the associated costs would increase. Hence, the target is to reduce the cost of the ENS without any large increase in the RCS cost. To get more realistic results, the effect of fuse failure probability (FFP) and power equipment aging are also included for evaluation in the presence of the RCS.

The main objective function is

$$G_i = \sum_{i=1}^{n} (ENS)_i \times K \times CPV_1 \tag{7}$$

where, $(ENS)_i$ is the energy not served for the i^{th} LP, K is the cost of per unit energy not supplied and CPV_1 is the cumulative present value of the ENS cost. The cumulative present value method has been applied to evaluate the total cost and benefits during the economic life cycle of the equipment [16]. The proposed objective function considers the interest rate, inflation rate, load growth and economic lifetime of the equipment.

CPV_1 is calculated as:

$$CPV_1 = \frac{1-(PV_1)^{EL}}{1-PV_1} \tag{8}$$

where,

$$PV_1 = \frac{\left(1+\frac{R_{\inf}}{100}\right)\left(1+\frac{LG}{100}\right)}{\left(1+\frac{R_{\text{int}}}{100}\right)} \tag{9}$$

Another objective function is proposed to reduce the cost of the RCSs. It is given as:

$$G_2 = \sum_{j=1}^{N_s} \left(\text{Cost}_{ins}^{RCS}\right)_j + \sum_{j=1}^{N_s} \left(\text{Cost}_{OM}^{RCS}\right)_j \times CPV_2 \tag{10}$$

where, CPV_2 and PV_2 are respectively given as

$$CPV_2 = \frac{1-(PV_2)^{EL}}{1-PV_2} \tag{11}$$

$$PV_2 = \frac{\left(1+\frac{R_{\inf}}{100}\right)}{\left(1+\frac{R_{\text{int}}}{100}\right)} \tag{12}$$

In (11) and (12), the economic lifespan of the equipment is denoted by EL, R_{int} is the interest rate, R_{inf} is the inflation rate and LG represents the growth of the load.

4. Mathematical formulation

4.1. Modeling for the failure rate

The accuracy of the failure rate model for the equipment in the power system determines the reliability of the results of the reliability assessment. The equipment failure rate is typically assumed to be constant, which prevents a real-time assessment of system reliability [22]. The bathtub curve, which is seen in Figure 2, can be used to understand and validate the relationship between the failure rate and life cycle. The full life cycle of the equipment has three stages, i.e., periods of infant mortality, stabilization and wear out. The initial/infant mortality period is not considered here and the failure rate will remain stable during the stabilization time as shown below in (13).

$$\lambda_1(t) = \lambda_C \tag{13}$$

where, λ_c is the constant failure rate.

The system becomes increasingly unreliable during the aging period as the failure rate changes over time. The Weibull Distribution function [1] is widely used to measure the rate of failure during the aging process, and it is given as

$$\lambda_2(t) = \lambda_C + \lambda_V \times \beta_2 \times t^{\beta_2 - 1} \tag{14}$$

where, λ_v and β_2 are the variable failure rate and aging coefficient, respectively.

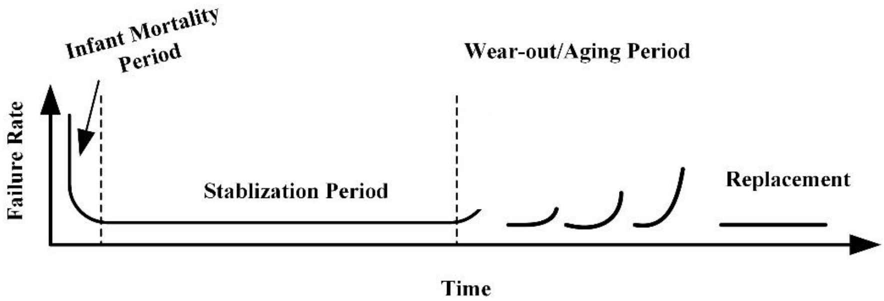

Figure 2. Bathtub curve with failure rate and asset management.

The majority of studies considered the constant failure rates of conventional power equipment. This type of failure rate model is considered as model-1 and the failure rate model considering the aging is termed as model-2 in this article. As discussed in [1], λ_C and λ_V are the constant and variable failure rates under various weather conditions. If the weather is considered as single-state weather, then λ_C can be considered equal to λ_V. The aging coefficient is β_2, and the higher value of β_2 reveals the fast-aging period of equipment. As this analysis has been done considering the single-state weather, we put $\lambda_C = \lambda_V$ and use $\beta_2 = 1.5$ in (14).

The life cycle of the feeder and transformer is taken as 15 years. The failure rates of model-1 and model-2 are listed in Table 2.

Table 2. Failure rates of model-1 and model-2.

Components	Failure rate of Model 1	Failure rate of Model 2
Feeder	0.065	0.443
Transformer	0.015	0.102

4.2. Modeling for load growth

Until now, the network's reliability has been assessed while assuming constant load. However, given the current state of technology and its rapid growth, load is also continuously rising. This study uses a straightforward 1% annual load growth rate for each category of load (residential, government/institutional, commercial, and small users), and it uses a 15-year evaluation period to reflect the equipment's ageing. With 1% growth, the load after 15 years is evaluate as

$$Load^{15} = L_{\text{int}} \times (1 + \%LG)^{t} \tag{15}$$

where, L_{int} is the initial load, t is the time of evaluation and $\%LG$ is the rate of load growth.

4.3. Modeling for fuse failure probability

The literature consists of a lot of models that evaluates the reliability including the relay's failure [23], but fuse modeling is different from relay modeling because the fuse does not have any assessment state when the current carrying element is up. Figure 3 represents the failure rate model of a fuse cutout.

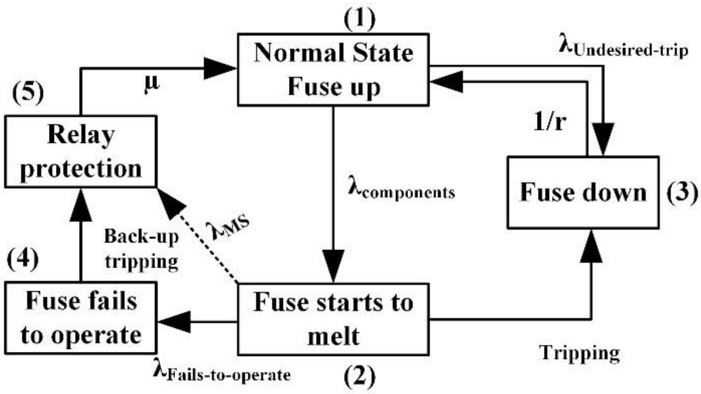

Figure 3. Model for fuse element.

In general, fuses are operated in a normal state. If a problem arises in the system, the fuse must operate by melting down in order to isolate the faulty portion [23]. However, occasionally fuses may stop working; in such a case, backup protection may be required to separate the faulty section. Fuse tripping can occasionally occur accidentally, de-energizing the system. In this case, the system goes straight from State (1) to State (3). Equation (16) calculates the failure rate for the system with FFP.

$$\lambda_{LP_i} = \lambda_{f_{100\%}} + \sum_{j=1}^{Nt} \lambda_{t_j} + \begin{Bmatrix} (\lambda_{fo}) \times (P_{fo}) \\ + (\lambda_{ff}) \times (P_{ff}) \end{Bmatrix} \tag{16}$$

where

$\lambda_{f_{100\%}}$	represents the failure rate when a fuse operates with 100% probability,
λ_{t_j}	represents the failure due to the j^{th} transformer,
λ_{f_o}	is the failure rate when the fuse operates,
P_{f_o}	is the probability that a fuse operates,
λ_{ff}	is the failure rate when a fuse fails to operate,
P_{ff}	is the probability that a fuse fails.

5. Solution strategy

The goal of this research is to reduce the ENS at the consumers end and achieve the optimal placement of RCSs by utilizing the greedy search algorithm. Although an alternative optimization method might be employed in this situation, the ability of this method to rapidly and accurately converge is the prime justification for its selection. A trade-off between the numbers and the cost of RCSs has resulted in improved reliability metrics. Figure 4 shows a flowchart for the greedy search optimization approach. The following steps should be taken:

Pseudo-code

Start

Input:
- *Feeder failure rate:* λ_f
- *Transformer failure rate:* λ_T
- *Restoration time:* r_s
- *Line length: L*
- *Interruption cost data:* C_i

Initialization: *for i = 1: M*

Evaluate $CPV_1 = \frac{1-(PV_1)^{EL}}{1-PV_1}$

Evaluate $PV_1 = \frac{\left(1+\frac{R_{\inf}}{100}\right)\left(1+\frac{LG}{100}\right)}{\left(1+\frac{R_{\text{int}}}{100}\right)}$

Computation: λ_{LP}, r_{LP}, U_{LP};

if i=M (no. of feeders in which an RCS is placed)

Evaluate: $G_1 = \sum_{i=1}^{n} (ENS)_i \times K \times CPV_1$ *else i = i+1;*

Optimization: *for j=1: N;*

Evaluate $PV_2 = \frac{\left(1+\frac{R_{\inf}}{100}\right)}{\left(1+\frac{R_{\text{int}}}{100}\right)}$

Evaluate $CPV_2 = \frac{1-(PV_2)^{EL}}{1-PV_2}$

compute: $G_2 = \sum_{j=1}^{N_s} \left(\text{Cos}\, t_{ins}^{RCS}\right)_j + \sum_{j=1}^{N_s} \left(\text{Cos}\, t_{OM}^{RCS}\right)_j \times CPV_2$

if G1 > G2

Display the optimal location of the RCS

else

Go for another location of RCS

end

end

end

end

6. Computational results

6.1. Network topology

The topology of the tested distribution network at bus 2 is shown in Figure 5. The investigated network is a component of the 6-bus RBTS system [22]. This network at bus 2 consists of four circuit breakers connected at the starting point of each feeder. There are four 11 kV feeders designated as F1, F2, F3 and F4, as well as 20 transformers, 14 sectionalizing switches, 20 fuses and 22 LPs that make up the network. A total of 1908 users are registered in the network as a whole. Tables 3 and 4 display the load statistics for various LPs and customers. It is evident that Feeders F1 and F4 have the highest loads relative to the other feeders, whereas Feeder F2 has the lowest loads (two consumers). Since both of the loads on Feeder F2 are major LPs and they do not require voltage transformation, they are both directly connected to the feeder. Reliability data for the system components is included in Table 5.

Table 3. Peak load in % for each sector [22].

Customer type	Peak load (MW)	Sector peak (%)
Residential	7.25	36.25
Small users	3.50	17.50
Govt. & Inst.	5.55	27.75
Commercial	3.70	18.50
Total	20	100

Table 4. Loading data for LPs [22].

Load points	Load at various LPs, MW	
	average	peak
1-3, 10, 11	0.535	0.8668
12, 17-19	0.450	0.7291
8	1.00	1.6279
9	1.15	1.8721
4, 5, 13, 14, 20, 21	0.566	0.9167
6, 7, 15, 16, 22	0.454	0.7500
Total	12.291	20.00

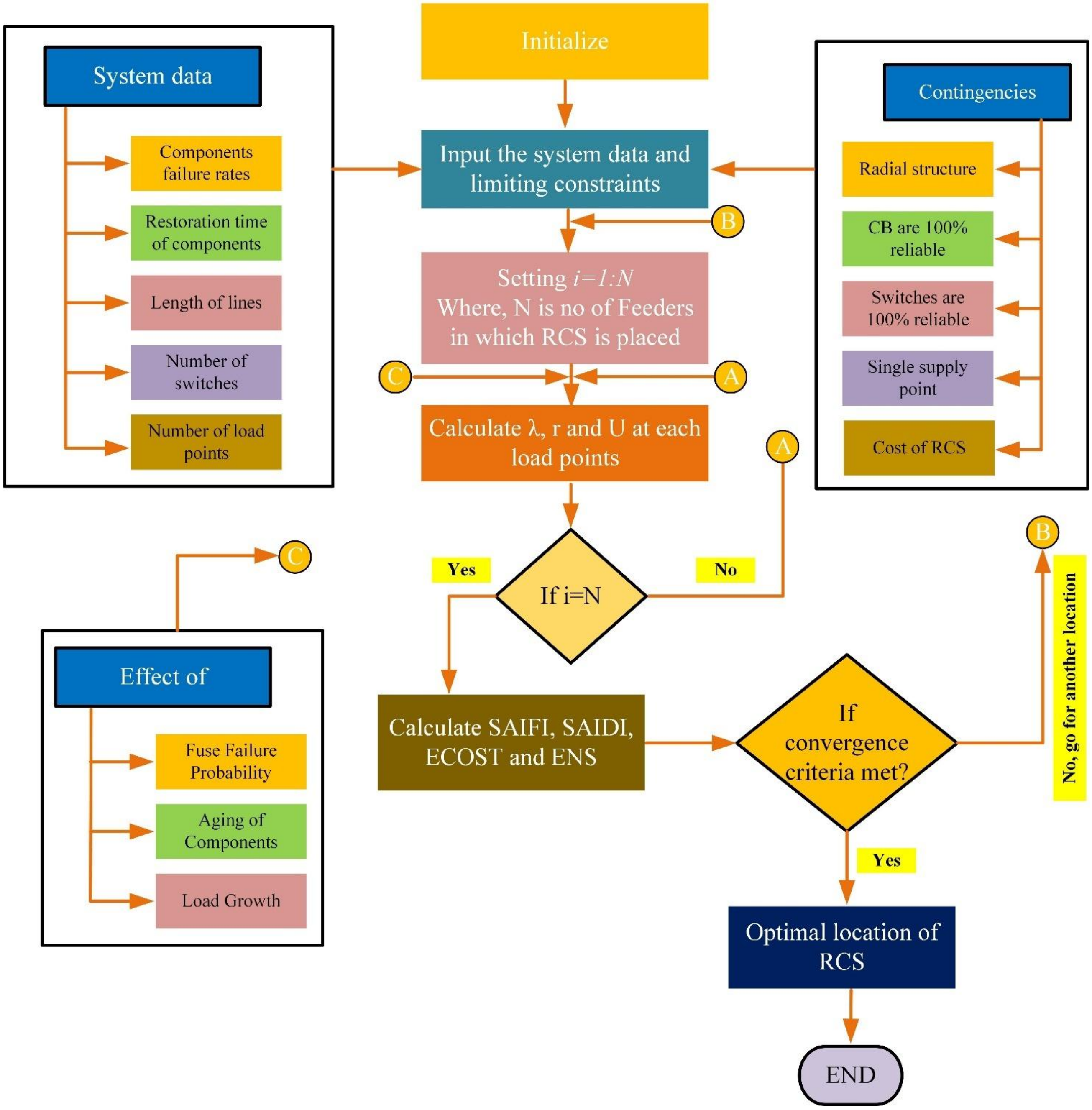

Figure 4. Flowchart for the greedy search algorithm.

Table 5. System reliability data [1].

Failure Rate (failure/yr/km)	Repair time (h)	Replacement time (h)	Switching time (h)
Feeder			
0.065	5	-	1
Transformer			
0.015	200	5	1

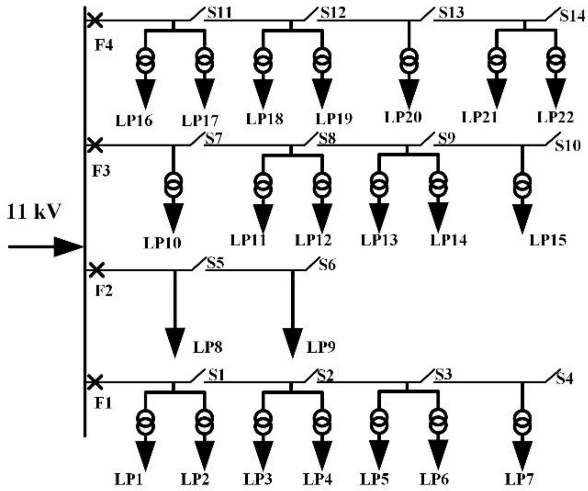

Figure 5. Distribution network at RBTS bus 2 [22].

The distribution network connected at bus 5 of the RBTS also consists of four feeders (F1, F2, F3 and F4) at 11 kV each. The network consists of 26 transformers, 17 sectionalizing switches, 26 fuses and 26 LPs. The total number of consumers in the network was set to be 2858. Figure 6 shows the topology for the distribution network at bus 5.

In this analysis, RCSs are associated with installation and maintenance costs which have considered to be USD 4433.60 and USD 166.26 for each RCS [2]. The cost of the ENS is taken as USD 5/kWh and the economic lifetime is considered as 15 years. The rate of inflation is assumed to be 8% and the rate of interest is assumed to be 5%. The load growth is also assumed to be 5%. The service restoration time for an RCS is taken to be 10 minutes in this analysis [2].

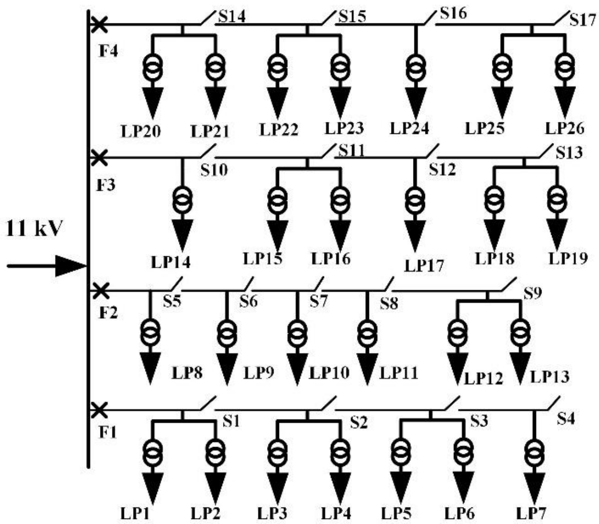

Figure 6. Distribution network at RBTS bus 5 [23].

Table 6 shows the results for installation of RCSs in the bus 2 network, and Table 7 shows the results for bus 5. From Table 6, it can be ascertained that the presence of an RCS does not affect the SAIFI, but it does reduce the SAIDI and END significantly. With RCSs the SAIDI decreased by

16.67% and the ENS decreased by 10.38% relative to those for the network without an automatic switch. Figures 7 and 8 represent a comparative pictorial representation of RCS cost and savings in terms of the ENS for bus 2 and bus 5 respectively. The results show a significant improvement in the reliability of the network in consideration of the installation and maintenance cost of RCS.

Further, placement of the RCSs in all feeders together reduces the SAIDI and ENS by 16.60% and 10.38%, respectively. In this case, 14 RCS were placed in the network; their cumulative present worth after 15 years of economic life was determined to be USD 1,05,364.56 and reduction in the cost of the ENS was determined to be USD 2,96,001.5.

Further, the effect of FFP with and without an automatic switch was examined on bus-2 network; the results are included in Appendices A1, A2 and A3. The analysis was done for 10%, 20% and 30% FFP with the effect of load growth for 15 years. The results revealed that inclusion of 10% FFP with RCSs coincides with SAIDI and ENS reduction of 19.85% and 15.70%, respectively. In this case, 14 RCS were placed in the network and their cumulative present worth after 15 years of economic life determined to be USD 1,05,364.56 and the reduction in the cost of the ENS was USD 2,99,491.98. As a continuation of the FFP analysis, the effects of feeder aging and distribution transformer aging were also analyzed. The results are presented in Table 8 and Table 9 below. There were respective reductions of 19.85% and 18.64% in the SAIDI and ENS with aging of the feeder and distribution transformer when the RCSs were placed at sectionalizing switches. The reduction in the cost of the ENS with an automatic switch is USD 25,09,541.73, while the cost of installation for 14 RCS was determined to be USD 1,05,364.56. The installation and maintenance costs for RCSs were determined to be much lower than the reduction in the cost of the ENS. Therefore, it is economical to replace all sectionalizing switches with RCSs.

Table 6. Analysis of RBTS bus-2 network with RCSs.

	SAIFI	SAIDI	ENS (kWh)	Cost of ENS (G1) (USD)	No. of RCSs	Cost of RCSs (G2) (USD)
No- RCS system	0.2482	0.6907	14,048.98	1,907,297.1	0	0
RCS in F1	0.2482	0.6517	13,328.34	1,809,463.05	4	30,104.16
RCS in F2	0.2482	0.6906	13,912.49	1,888,767.38	2	15,052.08
RCS in F3	0.2482	0.6527	13,416.05	1,821,370.91	4	30,104.16
RCS in F4	0.2482	0.6529	13,358.6	1,813,571.19	4	30,104.16
RCS in F1 & F2	0.2482	0.6517	13,191.96	1,790,947.7	6	45,156.24
RCS in F1 & F3	0.2482	0.6137	12,695.42	1,723,536.86	8	60,208.32
RCS in F1 & F4	0.2482	0.6140	12,638.07	1,715,751.51	8	60,208.32
RCS in F2 & F3	0.2482	0.6526	13,279.57	1,802,841.19	6	45,156.24
RCS in F2 & F4	0.2482	0.6529	13,222.22	1,795,055.84	6	45,156.24
RCS in F3 & F4	0.2482	0.6149	12,725.68	1,727,645	8	60,208.32
RCS in F1 F2 F3	0.2482	0.6137	12,559.04	1,705,021.51	10	75,260.4
RCS in F1 F2 F4	0.2482	0.6140	12,501.58	1,697,221.79	10	75,260.4
RCS in F1 F3 F4	0.2482	0.5760	12,005.15	1,629,825.32	12	90,312.48
RCS in F2 F3 F4	0.2482	0.6149	12,589.3	1,709,129.65	10	75,260.4
System with RCS	0.2482	0.5760	11,868.66	1,611,295.6	14	1,05,364.56

Table 7. Analysis of RBTS bus-5 network with RCSs.

	SAIFI	SAIDI	ENS (kWh)	Cost of ENS (G1) (USD)	No. of RCSs	Cost of RCSs (G2) (USD)
No-RCS system	0.2325	0.6262	13,234.89	1,796,776.37	0	0
RCS in F1	0.2325	0.5911	12,565.14	1,705,850.55	4	30,104.16
RCS in F2	0.2325	0.5893	12,674.42	1,720,686.26	5	37,630.2
RCS in F3	0.2325	0.6155	12,722.65	1,727,233.95	4	30,104.16
RCS in F4	0.2325	0.5971	12,667.38	1,719,730.5	4	30,104.16
RCS in F1 & F2	0.2325	0.5543	12,004.56	1,629,746.18	9	67,734.36
RCS in F1 & F3	0.2325	0.5804	12,052.79	1,636,293.87	8	60,208.32
RCS in F1 & F4	0.2325	0.5621	11,997.63	1,628,804.68	8	60,208.32
RCS in F2 & F3	0.2325	0.5786	12,162.07	1,651,129.58	9	67,734.36
RCS in F2 & F4	0.2325	0.5602	12,106.8	1,643,626.13	9	67,734.36
RCS in F3 & F4	0.2325	0.5864	12,155.14	1,650,188.08	8	60,208.32
RCS in F1 F2 F3	0.2325	0.5436	11,492.22	1,560,189.5	13	97,838.52
RCS in F1 F2 F4	0.2325	0.5252	11,437.05	1,552,700.31	13	97,838.52
RCS in F1 F3 F4	0.2325	0.5513	11,485.28	1,559,248	12	90,312.48
RCS in F2 F3 F4	0.2325	0.5495	11,594.56	1,574,083.71	13	97,838.52
System with RCS	0.2325	0.5145	10,924.7	1,483,143.63	17	1,27,942.68

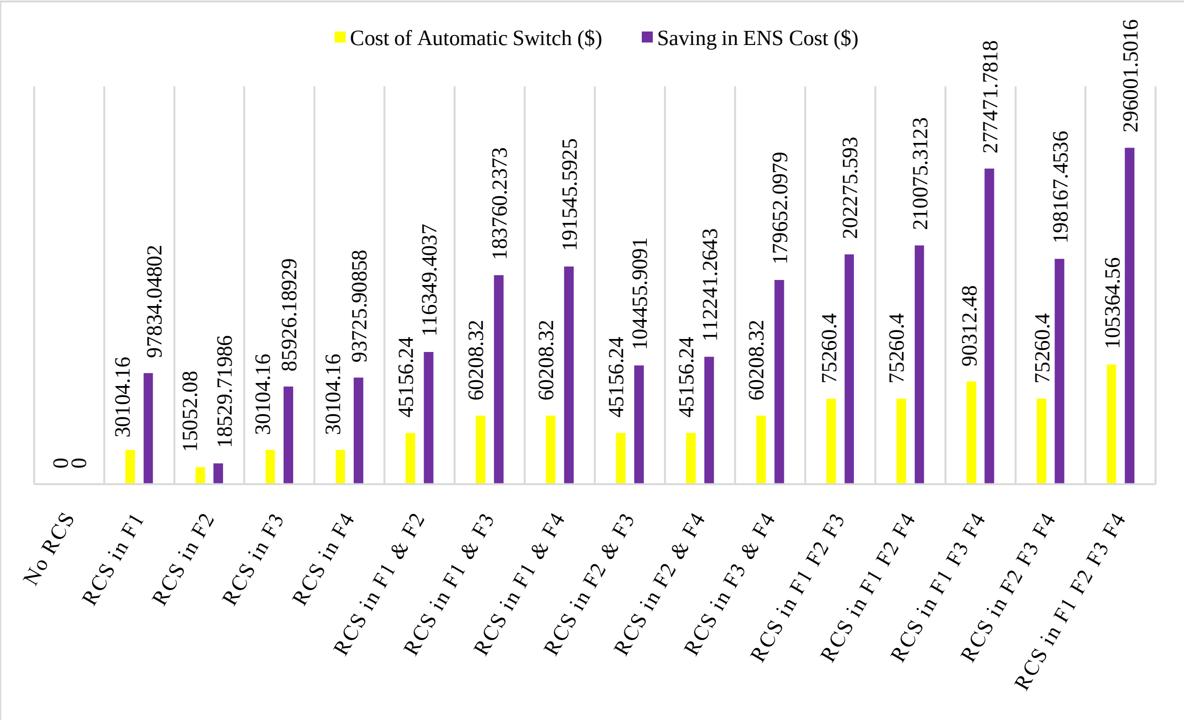

Figure 7. RCS cost and ENS saving for bus 2.

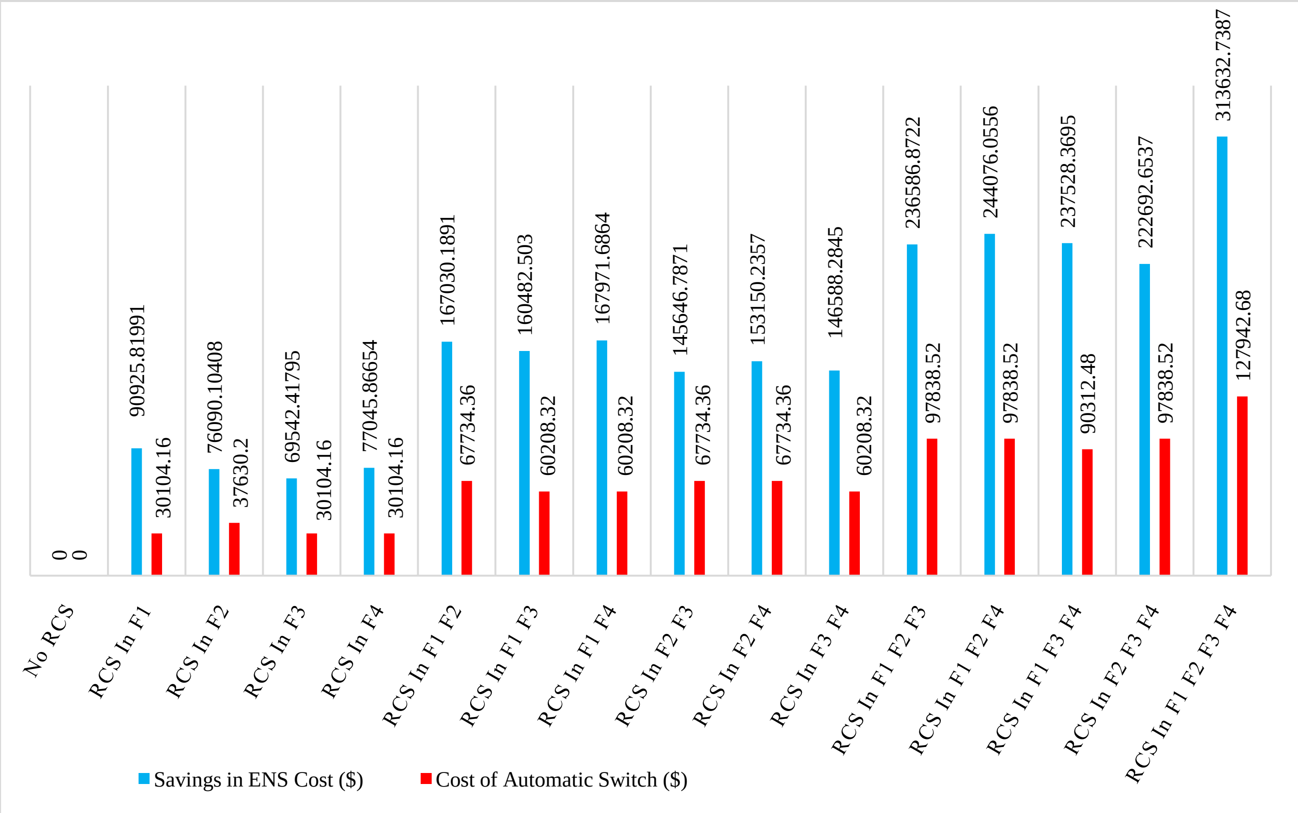

Figure 8. RCS cost and ENS saving for bus 5.

Table 8. Aging effect analysis for bus-2 RBTS network with no RCS, and given 10% FFP.

	SAIFI	SAIDI	ENS (kWh)	Cost of ENS (G1) (USD)	No. of RCSs	Cost of RCSs (G2) (USD)
Aging of transformer	0.4198	1.2099	23014.78	3,124,498.599	0	0
Aging of feeder and transformer	1.9327	4.9471	99178.50	13,464,527.57	0	0

Table 9. Aging effect analysis for bus-2 RBTS network with RCSs, and given a 10% FFP.

	SAIFI	SAIDI	ENS (kWh)	Cost of ENS (G1) (USD)	No. of RCSs	Cost of RCSs (G2) (USD)
Aging of transformer	0.4198	1.0247	19581.51	2,658,397.142	14	105364.56
Aging of feeder and transformer	1.9327	3.9647	80693.44	10,954,985.84	14	105364.56

7. Concluding remarks

This work extends the existing reliability evaluation procedure by incorporating RCSs in to the distribution network and accounting for the FFP and components aging. This paper shows how o determine the optimal location and number of RCS to reduce the cost of the ENS and the installation and maintenance cost of RCSs by using a greedy search optimization approach. The proposed approach has been applied to a distribution network given RBTS bus 2 and bus 5.

The results show that by installing 14 RCS in bus 2, ENS cost savings of USD 2,96,001.5 can be achieved, which is much more than the installation and maintenance cost (USD 1,05,364.56) of RCSs. Given the FFP and component aging, with 14 RCSs, the savings of USD 25,09,541.73 has been demonstrated. Similarly, with the installation of 17 RCSs in bus 5, ENS cost savings of USD 3,13,632.74 has been demonstrated while the installation and maintenance cost of RCSs were determined to be USD 1,27,942.68.

The results show a significant improvement in reliability of the network in the presence of RCSs.

Conflict of interest

The authors declare that there is no conflict of interest regarding this study.

References

1. Agarwal U, Jain N, Kumawat M, et al. (2020) Weibull Distribution Based Reliability Analysis of Radial Distribution System with Aging Effect of Transformer. *21st National Power Systems Conference (NPSC)*, 1–6. https://doi.org/10.1109/NPSC49263.2020.9331850
2. Siirto OK, Safdarian A, Lehtonen M, et al. (2015) Optimal distribution network automation considering earth fault events. *IEEE T Smart Grid* 6: 1010–1018. https://doi.org/10.1109/TSG.2014.2387471
3. Celli G, Pilo F (1999) Optimal sectionalizing switches allocation in distribution networks. *IEEE T Power Delivery* 14: 1167–1172. https://doi.org/10.1109/61.772388
4. Miu KN, Chiang HD, Yuan B, et al. (1998) Fast service restoration for large-scale distribution systems with priority customers and constraints. *IEEE T Power Syst* 13: 789–795. https://doi.org/10.1109/59.708643
5. Billinton R, Jonnavithula S (1996) Optimal switching device placement in radial distribution systems. *IEEE T Power Deliver* 11: 1646–1651. https://doi.org/10.1109/61.517529
6. Izadi M, Safdarian A (2019) Financial Risk Evaluation of RCS Deployment in Distribution Systems. *IEEE Systems Journal* 13: 692–701. https://doi.org/10.1109/JSYST.2018.2806992
7. Safdarian A, Farajollahi M, Fotuhi-Firuzabad M (2017) Impacts of remote-control switch malfunction on distribution system reliability. *IEEE T Power Syst* 32: 1572–1573. https://doi.org/10.1109/TPWRS.2016.2568747
8. Izadi M, Safdarian A (2017) Financial risk constrained remote controlled switch deployment in distribution networks. *IET Gener Transm Dis* 12: 1547–1553. https://doi.org/10.1049/iet-gtd.2017.0771
9. Izadi M, Safdarian A (2019) A MIP model for risk constrained switch placement in distribution networks. *IEEE T Smart Grid* 10: 4543–4553. https://doi.org/10.1109/TSG.2018.2863379
10. Izadi M, Farajollahi M, Safdarian A (2018) Switch deployment in distribution networks. *Electric distribution network management and control*, 179–233. https://doi.org/10.1007/978-981-10-7001-3_8
11. Alam A, Pant V, Das B (2020) Optimal placement of protective devices and switches in a radial distribution system with distributed generation. *IET Gener Transm Dis* 14: 4847–4858. https://doi.org/10.1049/iet-gtd.2019.1945

12. Bernardona DP, Sperandio M, Garcia VJ, et al. (2011) Methodology for allocation of RCS in distribution networks based on a fuzzy multi-criteria decision-making algorithm. *Electr Pow Syst Res* 81: 414–420. https://doi.org/10.1016/j.epsr.2010.10.010
13. Alam A, Alam MN, Pant V, et al. (2018) Placement of protective devices in distribution system considering uncertainties in loads, temporary and permanent failure rates and repair rates. *IET Gener Dist* 12: 1474–1485. https://doi.org/10.1049/iet-gtd.2017.0075
14. Alam A, Tariq M, Zaid M, et al. (2021) Optimal Placement of Reclosers in a Radial Distribution System for Reliability Improvement. *Electronics* 10: 3182. https://doi.org/10.3390/electronics10243182
15. Raoofat M (2011) Simultaneous allocation of DGs and remote controllable switches in distribution networks considering multilevel load model. *Int J Elec Power* 33: 1429–1436. https://doi.org/10.1016/j.ijepes.2011.06.023
16. Ray S, Bhattacharjee S, Bhattacharya A (2016) Optimal allocation of remote-control switches in radial distribution network for reliability improvement. *Ain Shams Eng J* 9: 403–414. https://doi.org/10.1016/j.asej.2016.01.001
17. Pombo AV, Murta-Pina J, Pires VF (2015) Multi-objective planning of distribution networks incorporating switches and protective devices using a memetic optimization. *Reliab Eng Syst Safe* 136: 101–108. https://doi.org/10.1016/j.ress.2014.11.016
18. Tippachon W, Rerkpreedapong D (2009) Multi-objective optimal placement of switches and protective devices in electric power distribution systems using ant colony optimization. *Electr Power Syst Res* 79: 1171–1178. https://doi.org/10.1016/j.epsr.2009.02.006
19. Bernardon DP, Sperandio M, Garcia VJ, et al. (2011) AHP decision-making algorithm to allocate remotely controlled switches in distribution networks. *IEEE T Power Deliver* 26: 1884–1892. https://doi.org/10.1109/TPWRD.2011.2119498
20. Esmaeilian HR, Fadaeinedjad R (2015) Distribution system efficiency improvement using network reconfiguration and capacitor allocation. *Int J Elec Power* 64: 457–468. https://doi.org/10.1016/j.ijepes.2014.06.051
21. Benavides AJ, Ritt M, Buriol LS, et al. (2013) An iterated sample construction with path relinking method: application to switch allocation in electrical distribution networks. *Comput Oper Res* 40: 24–32. https://doi.org/10.1016/j.cor.2012.05.006
22. Agarwal U, Jain N, Kumawat M, et al. (2022) An Assessment Procedure for Distribution Network Reliability Considering Load Growth. *Recent Advances in Power Systems*, 51–63. https://doi.org/10.1007/978-981-16-6970-5_5
23. Gilvanejad M, Abyaneh HA, Mazlumi K (2012) Fuse cutout allocation in radial distribution system considering the effect of hidden failures, *Int J Elec Power* 42: 575–582. https://doi.org/10.1016/j.ijepes.2012.04.038

Appendix

Appendix A

Table A1. Analysis of RBTS bus-2 network with RCS and a 10% FFP.

	SAIFI	SAIDI	ENS (kWh)	Cost of ENS (G1) (USD)	No. of RCSs	Cost of automatic switch (G2) (USD)
Base case	0.2482	0.6907	14048.98	1,907,297.102	0	0
Base case with FFP	0.2836	0.7261	14555.47	1,976,058.163	0	0
RCS in F1	0.2836	0.6764	13637.61	1,851,449.388	4	30104.16
RCS in F2	0.2836	0.7260	14403	1,955,359.461	2	15052.08
RCS in F3	0.2836	0.6796	13785.52	1,871,530.434	4	30104.16
RCS in F4	0.2836	0.6781	13683.11	1,857,625.962	4	30104.16
RCS in F1 & F2	0.2836	0.6764	13485.14	1,830,750.686	6	45156.24
RCS in F1 & F3	0.2836	0.6299	12867.67	1,746,921.659	8	60208.32
RCS in F1 & F4	0.2836	0.6284	12765.25	1,733,017.187	8	60208.32
RCS in F2 & F3	0.2836	0.6795	13633.69	1,850,917.916	6	45156.24
RCS in F2 & F4	0.2836	0.6780	13530.64	1,836,927.259	6	45156.24
RCS in F3 & F4	0.2836	0.6316	12913.27	1,753,112.596	8	60208.32
RCS in F1 F2 F3	0.2836	0.6299	12715.2	1,726,222.956	10	75260.4
RCS in F1 F2 F4	0.2836	0.5819	12612.78	1,712,318.484	10	75260.4
RCS in F1 F3 F4	0.2836	0.6284	11995.41	1,628,503.821	12	90312.48
RCS in F2 F3 F4	0.2836	0.6315	12760.7	1,732,399.529	10	75260.4
Base case with RCS	0.2482	0.5760	11868.66	1,611,295.601	14	105364.56
Base case with RCS under the effect of FFP	0.2836	0.5819	11842.95	1,607,805.119	14	105364.56

Table A2. Analysis of RBTS bus-2 network with RCS and a 20% FFP.

	SAIFI	SAIDI	ENS (kWh)	Cost of ENS (G1) (USD)	No of RCSs	Cost of RCSs (G2) (USD)
Base case	0.2482	0.6907	14048.98	1,907,297.102	0	0
Base case with FFP	0.3190	0.7615	15194.21	2,062,774.38	0	0
RCS in F1	0.3190	0.7011	14079.03	1,911,376.513	4	30104.16
RCS in F2	0.3190	0.7614	15025.66	2,039,892.33	2	15052.08
RCS in F3	0.3190	0.7065	14287.36	1,939,659.473	4	30104.16
RCS in F4	0.3190	0.7032	14139.87	1,919,635.885	4	30104.16
RCS in F1 & F2	0.3190	0.7011	13910.59	1,888,508.828	6	45156.24
RCS in F1 & F3	0.3190	0.6461	13172.28	1,788,275.971	8	60208.32
RCS in F1 & F4	0.3190	0.6429	13024.79	1,768,252.383	8	60208.32
RCS in F2 & F3	0.3190	0.7064	14118.81	1,916,777.424	6	45156.24
RCS in F2 & F4	0.3190	0.7032	13971.32	1,896,753.835	6	45156.24
RCS in F3 & F4	0.3190	0.6482	13233.01	1,796,520.979	8	60208.32

RCS in F1 F2 F3	0.3190	0.6460	13003.73	1,765,393.922	10	75260.4
RCS in F1 F2 F4	0.3190	0.6428	12856.24	1,745,370.333	10	75260.4
RCS in F1 F3 F4	0.3190	0.5878	12117.93	1,645,137.477	12	90312.48
RCS in F2 F3 F4	0.3190	0.6482	13064.46	1,773,638.929	10	75260.4
Base case with RCS	0.2482	0.5760	11868.66	1,611,295.601	14	105364.56
Base case with RCS under the effect of FFP	0.3190	0.5878	11949.39	1,622,255.427	14	105364.56

Table A3. Analysis of RBTS bus-2 network with RCS and a 30% FFP.

	SAIFI	**SAIDI**	**ENS (kWh)**	**Cost of ENS (G1) (USD)**	**No of RCSs**	**Cost of RCSs (G2) (USD)**
Base case	0.2482	0.6907	14048.98	1,907,297.102	0	0
Base case with FFP	0.3545	0.7969	15832.95	2,149,490.596	0	0
RCS in F1	0.3545	0.7258	14520.55	1,971,318.003	4	30104.16
RCS in F2	0.3545	0.7968	15648.32	2,124,425.199	2	15052.08
RCS in F3	0.3545	0.7334	14789.19	2,007,788.513	4	30104.16
RCS in F4	0.3545	0.7284	14596.62	1,981,645.808	4	30104.16
RCS in F1 & F2	0.3545	0.7257	14335.92	1,946,252.606	6	45156.24
RCS in F1 & F3	0.3545	0.6623	13476.79	1,829,615.92	8	60208.32
RCS in F1 & F4	0.3545	0.6573	13284.22	1,803,473.215	8	60208.32
RCS in F2 & F3	0.3545	0.7333	14604.56	1,982,723.117	6	45156.24
RCS in F2 & F4	0.3545	0.7283	14412	1,956,580.411	6	45156.24
RCS in F3 & F4	0.3545	0.6649	13552.86	1,839,943.725	8	60208.32
RCS in F1 F2 F3	0.3545	0.6622	13292.16	1,804,550.524	10	75260.4
RCS in F1 F2 F4	0.3545	0.6572	13099.7	1,778,422.182	10	75260.4
RCS in F1 F3 F4	0.3545	0.5938	12240.46	1,661,771.132	12	90312.48
RCS in F2 F3 F4	0.3545	0.6587	13255.23	1,799,537.445	10	75260.4
Base case with RCS	0.2482	0.5760	11868.66	1,611,295.601	14	105364.56
Base case with RCS under the effect of FFP	0.3545	0.5937	12055.83	1,636,705.736	14	105364.56