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Distribution Network Automation Considering Hidden Failure and Components Aging

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ABSTRACT

In the past decade, automated distribution network has governed importance as traditional distribution networks are not enough smart to satisfy the growing demand for reliable power supply. Being the less reliable and the only link between the utility and consumers, it is much urgent to enhance the distribution network reliability. The Remote-Controlled Switch (RCS) can be a good option to enhance the system reliability. It reduces the interruption duration, which intern will reduce the Energy not served and Expected cost of Interruption. This paper extends the present reliability assessment procedure to incorporate the RCS in distribution network using Greedy Search Algorithm. The optimal location and numbers of RCS has been evaluated with compromised cost. The effect of aging on equipment's failure rate and hidden failure rate of fuse are incorporated simultaneously in this article. The effectiveness of the proposed approach has been tested on distribution network connected at Bus-2 and Bus-5 of Roy Billionton Test System (RBTS). The results obtained show that optimally deployed RCS results in significant improvement of reliability indices for radial distribution network.

Keywords: Aging, Remote Controlled Switch, fuse failure probability, Radial distribution network, RBTS, Reliability.

1. INTRODUCTION

In present days, reliability analysis of distribution system is the topic of great concern. The requirement for continuous power supply increases in competitive market scenarios with the re-organization of the network. In the report of Canadian customer service utility, 80% (approximately) of customer interruption are due to the failure of any device in 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 of reliability enhancement, incorporation of the Automatic Switch can provide faster restoration of service during unexpected failure events and thereby it can improve the reliability. As depicted in [2], considering a fully automatic network will reduce the interruption cost by 80%, however, it is not economically justifiable to install the RCS at all the customer points. The installation and maintenance cost for large number of RCS would be high enough. Therefore, an optimal number of RCS is to be determined to minimize investment cost for maximization of reduction in cost of Energy Not Served (ENS). Hence, major research works in this area are briefed under this section.

Over the decades, the switch allocation issue has attracted researchers' attention, and numerous studies have been conducted [3–5]. With new trend in automation, the 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 has been used in [6]. This article calculates various financial risk indices such as volatility index, value at risk and conditional value at risk to quantify the risk. In [7], the malfunction probability of Remote-Controlled Switch (RCS) has been considered to extends the current reliability assessment procedure and the results shows that RCS improves the system reliability. The Non-Dominated Sorting Genetics Algorithm-II (NSGA-II) has been utilized in [8] for financial risk evaluation, associated with RCS placement and tested on RBTS Bus-4 system.

The Mixed Integer Programming (MIP) has been used in [9-10] to find the optimal location and numbers of RCS in distribution network for reliability enhancement. A new bi-directional model has been proposed in [11] for optimal placement of switches and protective devices in distribution network using GA with DG. In [12], fuzzy multi-criteria decision-making algorithm has been used to allocate the RCS in distribution network. In [13], Mixed Integer Non-Linear Programming (MINLP) 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 developed in [14], for the optimized allocation of reclosers in distribution network using GA approach. In [15], GA based method was used for simultaneous allocation of the DGs and RCSs in distribution network for power loss reduction and reliability improvement. The problem of optimal allocation of RCS in distribution network has been resolved using Differential Search (DS) algorithm in [16]. In [17-18], Memetic Optimization approach and Ant Colony Optimization has been utilized for multi-objective planning of distribution network with switches and protective devices, respectively. An Analytical Hierarchical Process (AHP) decision making algorithm has been implemented in [19] for allocation of RCS in distribution network. In [20], Esmaeilian and Fadaeinedjad implemented a Binary Gravitational Search Algorithm for reorganization of system and capacitor placement in distribution system for reliability enhancement. A new sample construction with path relinking method has been applied for the switch allocation in [21] for the reliability enhancement of distribution network. The reliability evaluation of distribution network considering the aging effect of components and load growth has been done in [22]. In [23], the

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optimal location of fuse cutouts considering the fuse failure probability has been done using Markov model.

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

1) This paper identifies the optimal location of the RCS using Greedy Search Algorithm in distribution network in a cost-effective manner.
2) Analyse the impact of fuse failure probability in presence of RCS on system as well as cost-worth reliability indices.
3) Analyse the impact of feeder and transformer aging on reliability parameters including RCS placement for real-time analysis of the system.

The outcomes of the proposed research will extend the present reliability evaluation procedure to incorporate all possible system contingencies. The organization of the paper is as below: Section II provides a brief detail about RCS and reliability indices for the system. Sections III and IV are dedicated to problem formulation and mathematical modeling, respectively. Section V represents the strategy used for finding the optimal location and numbers of RCS. Section VI is where the computational results are represented. Finally, Section VII concludes the article.

2. Reliability Indices and Remote-Controlled Switch

In recent trend of smart grid and modernization of existing distribution network, the automatic switch is proved to be a source of revolution. It can improve the service availability at consumer end as its switching time is much short. The RCS can be used as sectionalizing switch (normally close) as well as tie switches (Normally open). In radial distribution network, normally closed automatic switches are used to isolate the faulty section from rest of the system. Therefore, location of the automatic switch can improve the system reliability up 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. Repair time represents the time needed to repair the faulty section. Switching time represents the time required to restore the supply for healthy section by switching off the faulty part. Outage duration is considered on annual basis and it is calculated by either multiplication of failure rate with repair time or multiplication of failure rate with switching time.

Although, the RCS does not have any considerable impact on failure rate. However, the switching time, in presence of RCS is 10 minutes only, thereby, it will enhance the service availability by fast restoration of the supply. If a fault occurs at the downstream of the Load Point (LP) and no switch is available between them, then the LP will experience the repair time. In spite of this, if a normal

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switch is available between them, switching time will be applicable. If the automatic switch is connected at the place of normal switch, the switching time would reduce by a great extent and fast service restoration can be achieved.

With the help of failure rate, repair/switching time data and details about 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 focused in this work.

If the failure rate is denoted as λ (failure/yr./km), repair time as r (hours) and switching time as s (hours) then 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 energy not served is obtained as:

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

Other reliability indices are shown below in Table 1.

Table 1: 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)

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In distribution network, segments are branches of the network. In this structure, two branches may be connected through a switch in between them or may be connected with a load point. A load point will experience an interruption if,

- The segment connects the source and the load point.
- There isn't a fuse between the segment and the load point.

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

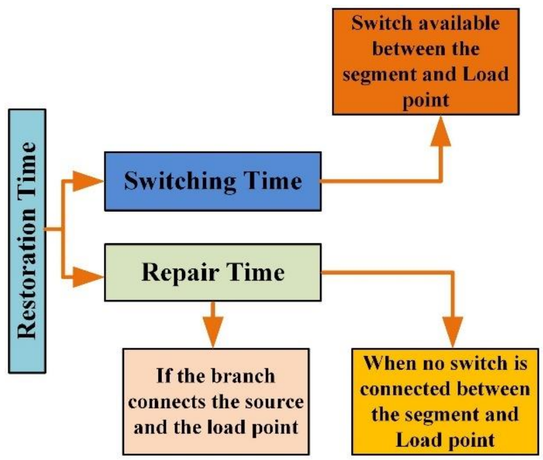

Fig. 1: Conditions for service restoration

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

3. Problem Statement

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

The main objective function is

$$G_1 = \sum_{i=1}^{n} (ENS)_i \times K \times CPV_1 \quad (7)$$

where, $(ENS)_i$ is the energy not served for the i^{th} load point, 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

(CPV) method has been applied to evaluate the total cost and benefits during the economic lifecycle of the equipment's [16]. The proposed objective function considers the interest rate, inflation rate, load growth and economic lifetime of the equipment's.

CPV_1 is calculated as:

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

Where,

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

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

$$G_2 = \sum_{j=1}^{N_s}\left(\text{Cos}\,t_{ins}^{RCS}\right)_j + \sum_{j=1}^{N_s}\left(\text{Cos}\,t_{OM}^{RCS}\right)_j \times CPV_2 \quad (10)$$

where, the CPV_2 and PV_2 are given as

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

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

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 in load.

4. MATHEMATICAL FORMULATION

4.1 FAILURE RATE MODEL OF POWER SYSTEM COMPONENT

The authenticity of the reliability assessment results depends on the precision of the power system equipment's failure rate model. Generally, the failure rate of equipment is taken as constant, which is not the real time evaluation of system reliability [22]. The relation between the failure rate and life cycle can be understood and validated with the Bath-Tub curve as shown in Fig. 2. There are 3 stages in the complete life cycle of the equipment. The infant mortality period, stabilization period and wear out period. 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).

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

where, λ_c is constant failure rate.

During the aging period, the failure rate varies with time and makes the system more unreliable. The two parameters Weibull Distribution function [1] is widely used to measure the rate of failure during the aging process and 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 variable failure rate and aging coefficient, respectively.

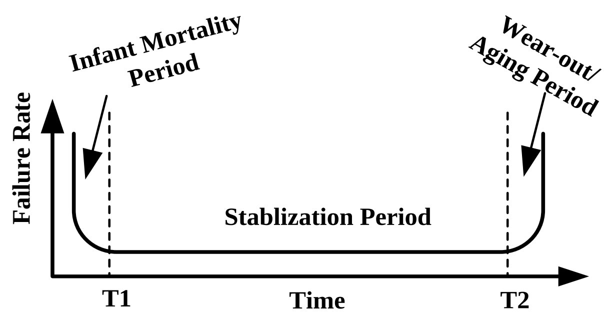

Fig. 2: Bathtub Curve

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

The life cycle of the feeder and transformer is taken 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

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Transformer	0.015	0.102

4.2 Modelling for Fuse Failure Probability

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

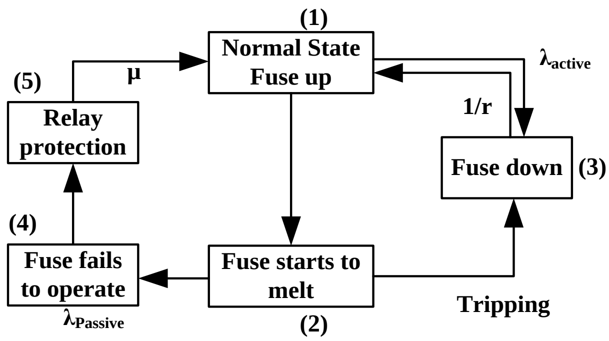

Fig. 3: Fuse Cutout Model

In general, fuse operated in normal state. Whenever any fault occurs in the system then fuse has to operate by melting down to isolate the faulty section [23]. However, sometimes it may happen that fuse fails to operate, and then it will be the responsibility of backup protection to isolate the faulty section. Sometimes, it may happen that fuse trips unintentionally and de-energies the system. In this situation, system moves to state (3) from state (1) directly. The eq. (15) calculates the failure rate for the system with fuse failure probability.

$$\lambda_{LP_i} = \lambda_{f_{100\%}} + \sum_{j=1}^{Nt} \lambda_{t_j} + \left\{ \begin{array}{l} (\lambda_{fo}) \times (P_{fo}) \\ + (\lambda_{ff}) \times (P_{ff}) \end{array} \right\} \qquad (15)$$

Where,

$\lambda_{f_{100\%}}$ represents the failure rate when fuse operates with 100% probability.

λ_{t_j} represents the failure rate due to j^{th} transformer.

λ_{fo} is failure rate when fuse operates.

P_{fo} is probability that fuse operates.

λ_{ff} is failure rate when fuse failed to operate.

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P_{ff} is probability that fuse fails.

5. SOLUTION STRATEGY

The goal of this research is to reduce the Energy Not Served at consumers end with the optimal placement of RCS, by utilizing the Greedy Search Algorithm. Although, alternative optimization method might be employed in this situation, the ability of this method to fast and accurately converge is the prime justification for its selection. A compromised selection between the numbers and the cost of RCS has resulted in an improved reliability metrics. Figure 4 shows a flow chart for the Greedy Search optimization approach. The following steps are 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 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

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Display the optimal location of RCS
else
Go for another location of RCS
end
end
end
end

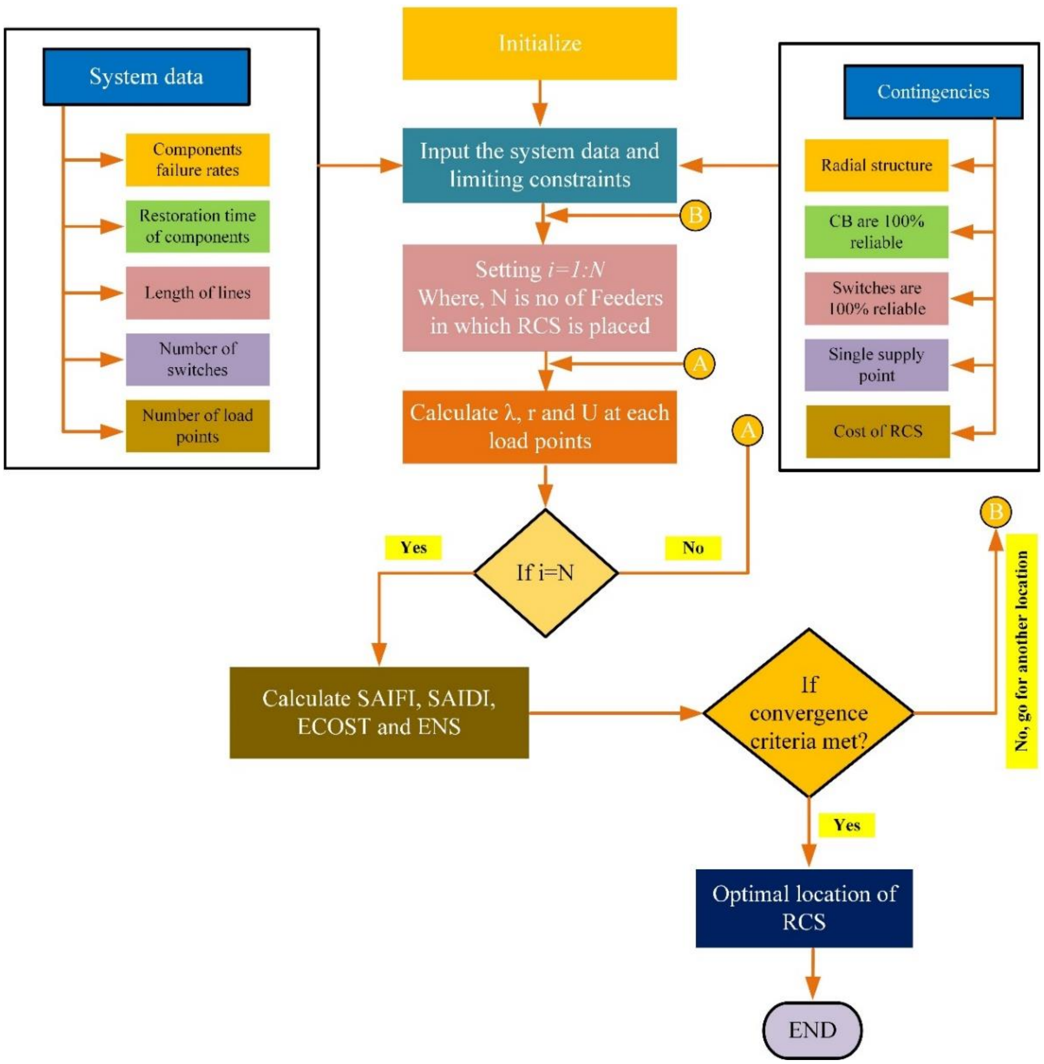

Fig 4: Flowchart for the Greedy Search Algorithm

6. Computational results

5.1 Network topology

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The topology of the evaluated distribution network at Bus-2 is shown in Fig. 5. The studied network is a part of RBTS 6-Bus system [22]. This network at Bus-2 consists of four circuit breakers connected at the starting point of each feeder. There are four feeders (F1, F2, F3 and F4) of 11 kV each. The network consists 20 transformers, 14 sectionalizing switches, 20 fuses and 22 load points. The total number of consumers at the network are 1908. The load data of various load points and consumers is shown in Table 3 and Table 4. It can be seen that F1 and F4 have the highest load as compared to other feeders and feeder F2 has the minimum load (2 consumers). Both loads of feeder F2 are directly connected to the feeder as these are large load points and don't require any transformation of voltage. Reliability data of 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 of load points [22]

Load points	**Load at various Load Points, 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

Table 5: System Reliability Data [1]

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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

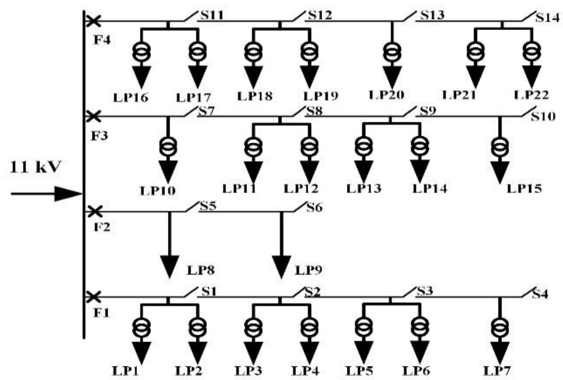

Fig 5: Distribution network at Bus-2 of RBTS [22]

The distribution network connected at Bus-5 of RBTS, also consists of four feeders (F1, F2, F3 and F4) of 11 kV each. The network consists 26 transformers, 17 sectionalizing switches, 26 fuses and 26 load points. The total number of consumers at the network are 2858. The fig. 6 shows the topology for the distribution network at Bus-5.

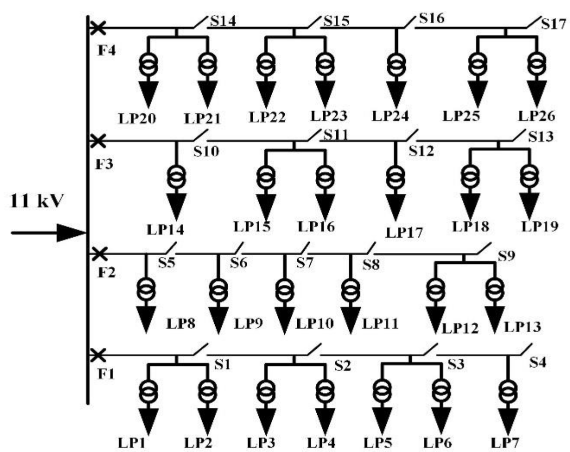

Fig 6: Distribution network at Bus-5 of RBTS [23]

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

Table 6 shows the results for installation of the RCS in Bus 2 network and table 7 shows the results for Bus 5. From table 6, it can be dictated that the RCS does not affects the system average interruption frequency index (SAIFI) but reduces the system average interruption duration index (SAIDI) and energy not supplied (ENS) significantly. With RCS, the SAIDI reduced by 16.67% and ENS reduced by 15.52% when compared to the network without automatic switch. Figure 7 and 8 represents a comparative pictorial representation of RCS cost and savings in ENS for Bus2 and Bus 5 respectively. The results represent a significant improvement in the reliability of network comparative with installation and maintenance cost of RCS.

Further, placement of the RCS in all feeders together, reduces the SAIDI and ENS by 16.60% and 15.52%, respectively. In this case, 14 RCS are placed in the network and their cumulative present worth after 15 years of economic life is US $ 1,05,364.56 and reduction in the cost of ENS is US $ 2,79,761.765.

Table 6: Analysis of RBTS Bus 2 network with Remote controlled switch

	SAIFI	**SAIDI**	**ENS (kWh)**	**Cost of ENS (G1) ($)**	**No. of RCS**	**Cost of RCS (G2) ($)**
System without RCS	0.2482	0.6907	13278.2	1802655.735	0	0
RCS in F1	0.2482	0.6517	12597.1	1710189.224	4	30104.16
RCS in F2	0.2482	0.6906	13149.2	1785142.624	2	15052.08
RCS in F3	0.2482	0.6527	12680.0	1721443.774	4	30104.16
RCS in F4	0.2482	0.6529	12625.7	1714071.976	4	30104.16
RCS in F1 & F2	0.2482	0.6517	12468.2	1692689.69	6	45156.24
RCS in F1 & F3	0.2482	0.6137	11998.9	1628977.263	8	60208.32
RCS in F1 & F4	0.2482	0.6140	11944.7	1621619.042	8	60208.32
RCS in F2 & F3	0.2482	0.6526	12551.0	1703930.663	6	45156.24

RCS in F2 & F4	0.2482	0.6529	12496.8	1696572.441	6	45156.24
RCS in F3 & F4	0.2482	0.6149	12027.5	1632860.015	8	60208.32
RCS in F1 F2 F3	0.2482	0.6137	11870.0	1611477.729	10	75260.4
RCS in F1 F2 F4	0.2482	0.6140	11815.7	1604105.931	10	75260.4
RCS in F1 F3 F4	0.2482	0.5760	11346.5	1540407.081	12	90312.48
RCS in F2 F3 F4	0.2482	0.6149	11898.6	1615360.48	10	75260.4
System with RCS	0.2482	0.5760	11217.5	1522893.97	14	105364.56

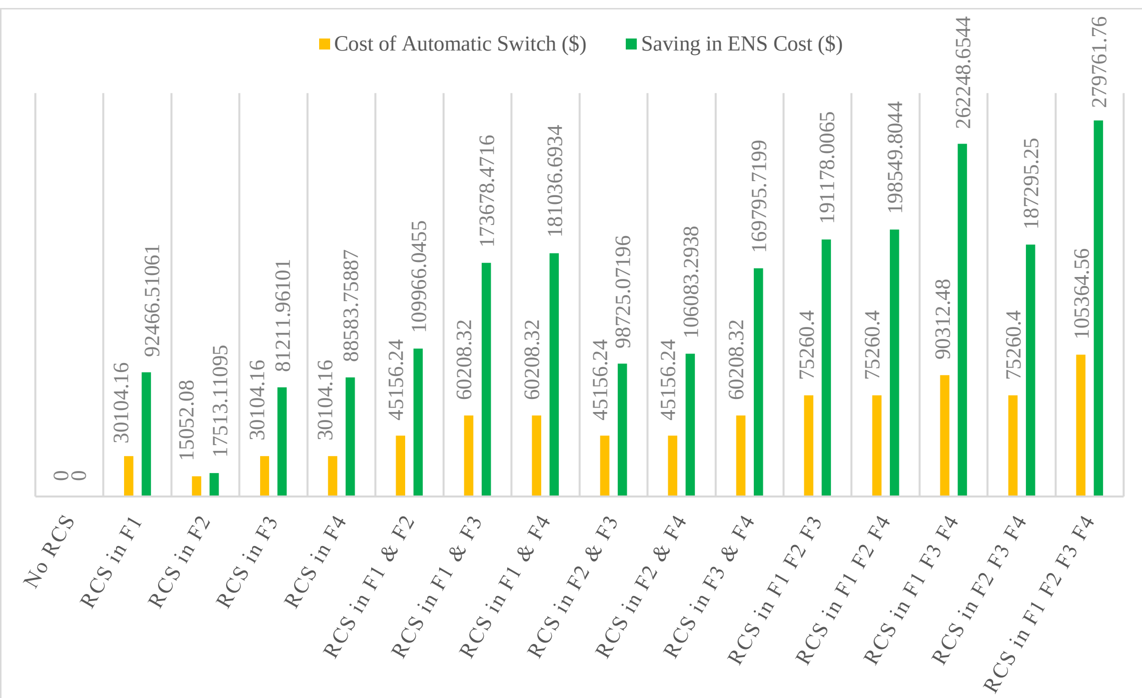

Fig. 7: Graphical representation of RCS cost and saving in ENS for Bus-2

Table 7: Analysis of RBTS Bus 5 network with Remote controlled switch

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	SAIFI	SAIDI	ENS (kWh)	Cost of ENS (G1) ($)	No. of Automatic switches	Cost of Automatic Switch (G2) ($)
System without RCS	0.2325	0.6262	12595.6	1709985.584	0	0
RCS in F1	0.2325	0.5911	11958.2	1623451.809	4	30104.16
RCS in F2	0.2325	0.5893	12062.2	1637570.906	5	37630.2
RCS in F3	0.2325	0.6155	12108.1	1643802.315	4	30104.16
RCS in F4	0.2325	0.5971	12055.5	1636661.311	4	30104.16
RCS in F1 & F2	0.2325	0.5543	11424.7	1551023.556	9	67734.36
RCS in F1 & F3	0.2325	0.5804	11470.6	1557254.965	8	60208.32
RCS in F1 & F4	0.2325	0.5621	11418.1	1550127.536	8	60208.32
RCS in F2 & F3	0.2325	0.5786	11574.6	1571374.062	9	67734.36
RCS in F2 & F4	0.2325	0.5602	11522	1564233.057	9	67734.36
RCS in F3 & F4	0.2325	0.5864	11568	1570478.042	8	60208.32
RCS in F1 F2 F3	0.2325	0.5436	10937.1	1484826.711	13	97838.52
RCS in F1 F2 F4	0.2325	0.5252	10884.6	1477699.283	13	97838.52
RCS in F1 F3 F4	0.2325	0.5513	10930.5	1483930.692	12	90312.48
RCS in F2 F3 F4	0.2325	0.5495	11034.5	1498049.789	13	97838.52
System with RCS	0.2325	0.5145	10397	1411502.438	17	127942.68

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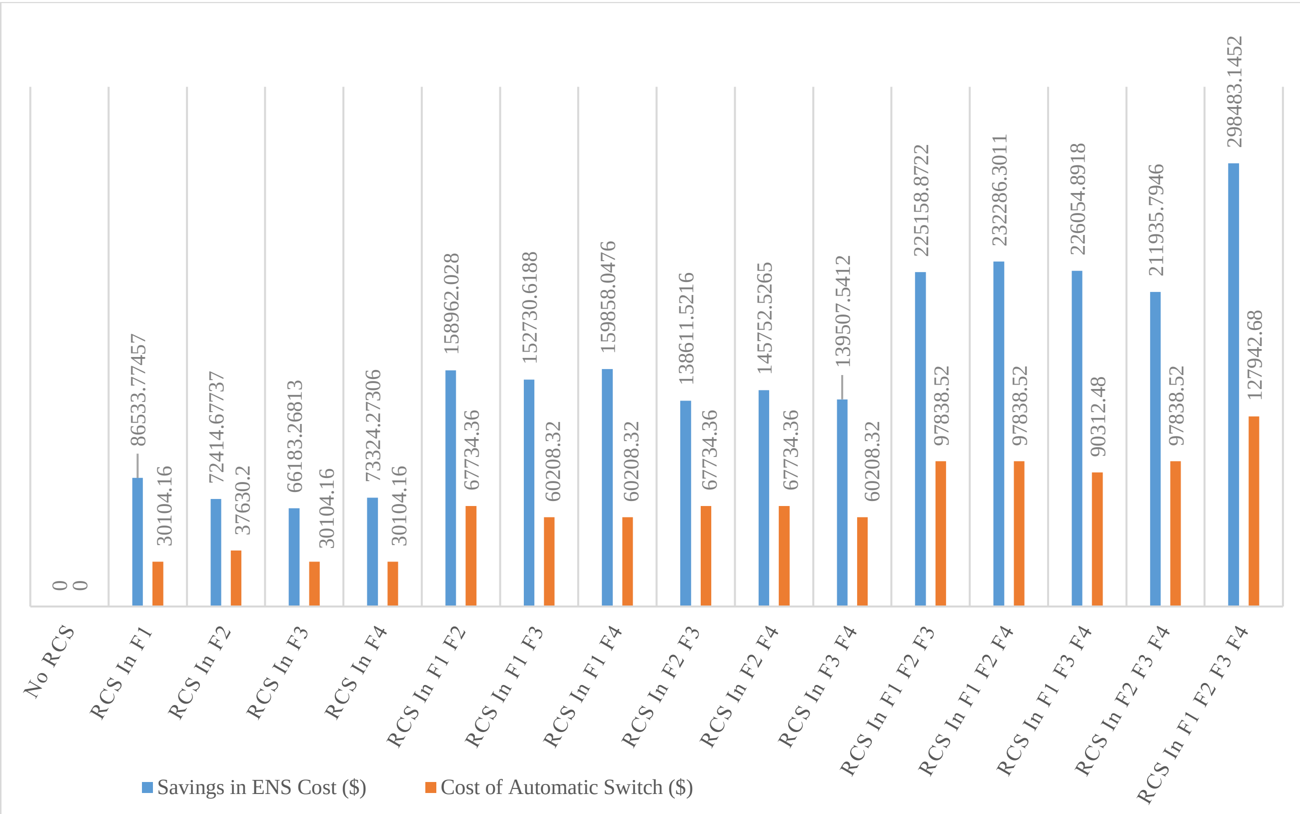

Fig. 8: Graphical representation of RCS cost and saving in ENS for Bus-5

Further, the effect of fuse failure probability with and without automatic switch is examined on Bus 2 network and the results are included in Appendix A1, A2 and A3. The analysis is done for 10%, 20% and 30% failure probability of fuse. The results revel that inclusion of 10 percent of fuse failure probability with RCS, the SAIDI and ENS reduced by 19.85% and 18.64%, respectively. In this case, 14 RCS are placed in the network and their cumulative present worth after 15 years of economic life is US $ 1,05,364.56 and the reduction in the cost of ENS is US $ 3,28,486.226. In continuation of fuse failure probability analysis, the effect of feeder aging and distribution transformer aging is also analyzed. The results are represented in Table 8 and Table 9 below. There is reduction of 19.85% and 18.63% in SAIDI and ENS with ageing effect of feeder and distribution transformer when the RCS is placed at sectionalizing switches. The reduction in the cost of ENS with automatic switch is US $ 23,71,859 while the cost of installation for 14 RCS is 1,05,364.56 $. The installation and maintenance for RCS is very less in comparison to the reduction in the cost of ENS. Therefore, it is economical to replace all the sectionalizing switches with RCS.

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Table 8: Aging effect Analysis of RBTS Bus 2 network without Remote controlled switch under the effect of Fuse Failure Probability (10%)

	SAIFI	SAIDI	ENS (kWh)	Cost of ENS (G1) (US $)	No of RCS	Cost of RCS (G2) (US $)
Aging of transformer	0.4198	1.2099	21,752.1	29,53,077.06	0	0
Aging of feeder and transformer	1.9327	4.9471	93,737.2	1,27,25,813.83	0	0

Table 9: Aging effect Analysis of RBTS Bus 2 network with Remote controlled switch under the effect of Fuse Failure Probability (10%)

	SAIFI	SAIDI	ENS (kWh)	Cost of ENS (G1) (US$)	No of RCS	Cost of RCS (G2) (US $)
Aging of transformer	0.4198	1.0247	18,507.2	25,12,547.651	14	105364.56
Aging of feeder and transformer	1.9327	3.9647	76,266.3	1,03,53,954.83	14	105364.56

7. CONCLUDING REMARKS

This work extends the present reliability evaluation procedure by incorporating the RCS in distribution network under the effect of fuse failure probability and components aging. This paper provides the optimal location and numbers of RCS to reduce the cost of Energy Not Served and installation and maintenance cost of RCS using Greedy Search Optimization approach. The proposed approach has been demonstrated on the distribution network at RBTS Bus 2 and Bus 5.

The results show that by installing 14 RCS in Bus 2, a saving of 2,79,761.76 $ has been achieved in the cost of ENS, which is much more than the installation and maintenance cost (1,05,364.56 $) of RCS. Under the effect of fuse failure probability and components aging, with 14 RCS, the savings of 23,71,859 $ has been achieved. Similarly, with installation of 17 RCS in Bus 5, saving of 2,98,483.15 $ has been obtained in the cost of ENS while the installation and maintenance cost of RCS is 1,27,942.68 $.

The results show a significant improvement in reliability of the network in the presence of Remote-Controlled Switches.

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Appendix A

Table A1: Analysis of RBTS Bus 2 network with Remote controlled switch under the effect of Fuse Failure Probability (10%)

	SAIFI	SAIDI	ENS (kWh)	Cost of ENS (G1) (US $)	No. of RCS	Cost of Automatic Switch (G2) ($)
Base case	0.2482	0.6907	13278.2	18,02,655.735	0	0
Base case with FFP	0.2836	0.7261	13756.9	18,67,644.31	0	0
RCS in F1	0.2836	0.6764	12889.4	17,49,872.033	4	30104.16
RCS in F2	0.2836	0.7260	13612.8	18,48,081.215	2	15052.08
RCS in F3	0.2836	0.6796	13029.2	17,68,851.358	4	30104.16
RCS in F4	0.2836	0.6781	12932.4	17,55,709.737	4	30104.16
RCS in F1 & F2	0.2836	0.6764	12745.3	17,30,308.938	6	45156.24
RCS in F1 & F3	0.2836	0.6299	12161.7	16,51,079.081	8	60208.32
RCS in F1 & F4	0.2836	0.6284	12064.9	16,37,937.46	8	60208.32
RCS in F2 & F3	0.2836	0.6795	12885.7	17,49,369.719	6	45156.24
RCS in F2 & F4	0.2836	0.6780	12788.3	17,36,146.642	6	45156.24
RCS in F3 & F4	0.2836	0.6316	12204.8	16,56,930.361	8	60208.32
RCS in F1 F2 F3	0.2836	0.6299	12017.6	16,31,515.986	10	75260.4
RCS in F1 F2 F4	0.2836	0.5819	11920.8	16,18,374.364	10	75260.4
RCS in F1 F3 F4	0.2836	0.6284	11337.3	15,39,158.084	12	90312.48
RCS in F2 F3 F4	0.2836	0.6315	12060.6	16,37,353.689	10	75260.4

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Base case with RCS	0.2482	0.5760	11217.5	15,22,893.97	14	105364.56
Base case with RCS under the effect of FFP	0.2836	0.5819	11193.2	15,19,594.988	14	105364.56

Table A2: Analysis of RBTS Bus 2 network with Remote controlled switch under the effect of Fuse Failure Probability (20%)

	SAIFI	**SAIDI**	**ENS (kWh)**	**Cost of ENS (G1) (US $)**	**No of RCS**	**Cost of RCS (G2) (US $)**
Base case	0.2482	0.6907	13278.2	18,02,655.735	0	0
Base case with FFP	0.3190	0.7615	14360.6	19,49,602.954	0	0
RCS in F1	0.3190	0.7011	13306.6	18,06,511.335	4	30104.16
RCS in F2	0.3190	0.7614	14201.3	19,27,976.299	2	15052.08
RCS in F3	0.3190	0.7065	13503.5	18,33,242.587	4	30104.16
RCS in F4	0.3190	0.7032	13364.1	18,14,317.566	4	30104.16
RCS in F1 & F2	0.3190	0.7011	13147.4	17,84,898.255	6	45156.24
RCS in F1 & F3	0.3190	0.6461	12449.6	16,90,164.543	8	60208.32
RCS in F1 & F4	0.3190	0.6429	12310.2	16,71,239.523	8	60208.32
RCS in F2 & F3	0.3190	0.7064	13344.2	18,11,615.931	6	45156.24
RCS in F2 & F4	0.3190	0.7032	13204.8	17,92,690.911	6	45156.24
RCS in F3 & F4	0.3190	0.6482	12507.0	16,97,957.199	8	60208.32
RCS in F1 F2 F3	0.3190	0.6460	12290.3	16,68,537.888	10	75260.4

RCS in F1 F2 F4	0.3190	0.6428	12150.9	16,49,612.867	10	75260.4
RCS in F1 F3 F4	0.3190	0.5878	11453.1	15,54,879.155	12	90312.48
RCS in F2 F3 F4	0.3190	0.6482	12347.7	16,76,330.543	10	75260.4
Base case with RCS	0.2482	0.5760	11217.5	15,22,893.97	14	105364.56
Base case with RCS under the effect of FFP	0.3190	0.5878	11293.8	15,33,252.5	14	105364.56

Table A3: Analysis of RBTS Bus 2 network with Remote controlled switch under the effect of Fuse Failure Probability (30%)

	SAIFI	**SAIDI**	**ENS (kWh)**	**Cost of ENS (G1) ($)**	**No of RCS**	**Cost of RCS (G2) (US $)**
Base case	0.2482	0.6907	13278.2	18,02,655.735	0	0
Base case with FFP	0.3545	0.7969	14964.3	20,31,561.598	0	0
RCS in F1	0.3545	0.7258	13723.9	18,63,164.212	4	30104.16
RCS in F2	0.3545	0.7968	14789.8	20,07,871.382	2	15052.08
RCS in F3	0.3545	0.7334	13977.8	18,97,633.816	4	30104.16
RCS in F4	0.3545	0.7284	13795.8	18,72,925.396	4	30104.16
RCS in F1 & F2	0.3545	0.7257	13549.4	18,39,473.996	6	45156.24
RCS in F1 & F3	0.3545	0.6623	12737.4	17,29,236.43	8	60208.32
RCS in F1 & F4	0.3545	0.6573	12555.4	17,04,528.009	8	60208.32
RCS in F2 & F3	0.3545	0.7333	13803.3	18,73,943.6	6	45156.24
RCS in F2 & F4	0.3545	0.7283	13621.3	18,49,235.18	6	45156.24
RCS in F3 & F4	0.3545	0.6649	12809.3	17,38,997.613	8	60208.32
RCS in F1 F2 F3	0.3545	0.6622	12562.9	17,05,546.214	10	75260.4
RCS in F1 F2 F4	0.3545	0.6572	12381.0	16,80,851.37	10	75260.4
RCS in F1 F3 F4	0.3545	0.5938	11568.9	15,70,600.227	12	90312.48

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RCS in F2 F3 F4	0.3545	0.6587	12528.0	17,00,808.17	10	75260.4
Base case with RCS	0.2482	0.5760	11217.5	15,22,893.97	14	105364.56
Base case with RCS under the effect of FFP	0.3545	0.5937	11394.4	15,46,910.011	14	105364.56