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Reliability Analysis of Switch Placement in Radial Distribution Network Considering Failure Probability

Manish Kumar Madhav* & K B Yadav

Department of Electrical Engineering, National Institute of Technology, Jamshedpur 831 014, India

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A comprehensive reliability assessment of radial distribution networks (RDN) by examining the operational impact and failure probability of protective devices such as isolators, fuses, and remote-controlled switches (RCS). The study starts with analytical evaluation of the 4-bus RDN and demonstrates the absence of protection causes complete feeder outages for any interruption. Reliability is significantly improved when fuses and isolators are added, as they enable selective isolation and faster service restoration. The work further investigates the practical scenario in which protective devices may fail, and results show notable deterioration in reliability indices when considering switch failure probability. To address this, a genetic algorithm (GA)-based optimization model is proposed for the optimal placement of isolators and RCS while explicitly incorporating their failure rates. The proposed method aims to minimize total system cost, including investment and customer interruption cost. The proposed method is tested on a modified IEEE 34-bus network confirms that 17 protective devices provide the optimal trade-off between economic investment, interruption reduction, and overall system reliability, whereas additional devices offer negligible improvement. The findings highlight the critical importance of incorporating realistic switch reliability during planning, ensuring accurate estimation of network performance and enhancing distribution system resilience.

Keywords: Distribution network, Isolators, Switch failure probability, Genetic algorithm, Reliability indices

1 Introduction

The prime purpose of the distribution system is to offer power to its consumers as cost-effectively as possible and with a suitable degree of reliability and quality. A power system having so many buses, generators, feeders, capacitor banks, loads, etc. connected makes its network most complex[1-5]. The electrical power system is mainly divided into generation, transmission, and distribution systems. Loads are highly random but electrical engineers are continuously trying to predict their characteristics[6-10]. Whereas the distribution system is a link between generating stations and consumers, it is also found that about 80 % of the fault occurs on the distribution side only[11-12]. This is not possible due to random apparatus and system failures, which are normally beyond the control of electrical engineers. The electrical power supply usually comprises a very complex and extremely integrated system[13-18]. If any of these components fail, there will be supply outages that affect a small number of individuals or cause massive, catastrophic disruptions. It has considered the location and size of the distributed generation in distribution network but reliability, protection and security did not consider[19-20]. The researchers utilised sectionalizer switch (SS) using optimization technique for optimal location but failure of switches did not consider[21-22]. They have optimized the DG and switches in distribution network using GA and PSO for the reliability analysis[23-25].

They focused on optimal placement of automatic switches assuming ideal device operation and considered sectionalizing switch failure, but economic trade-offs and multiple protection schemes were not analysed[26-27]. It introduced probabilistic interruption costs; however, the combined impact of device failure probability and optimal switch number remains insufficiently explored[28]. In today’s power systems, distribution companies face continued pressure to provide uninterrupted, high-quality power at competitive prices in compliance with consumer expectations as well as very stiff regulatory mandates and the most crucial link in between utilities and end users, where any disruptions are observed by customers almost instantly[29-30]. They have optimized the optimal location of isolators in 59 and 34 bus radial distribution system using hybrid GA[31]. Reliability is severely impacted by the fault in the

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*Corresponding author: E-mail: manishh.madhav@gmail.com

network, the failures of generation units, and malfunction of other critical power system components.

The researchers applied a Markov-based method to evaluate reliability considering component failure rates, but without addressing switch placement[32]. Reliability into switch planning for smart distribution systems, though switch maloperation effects were not explicitly modelled[33]. The optimal number and locations of RCSs minimize cost while maintaining performance, considering load growth and hidden fuse failures effects for system reliability[34].

The various researchers have purposed the reliability evaluation technique as well as work for the enhancement of the reliability of the system. To enhance the reliability of distribution network (DN) various method has been purposed by them. Optimal placement of switches such as isolators, fuse, circuit breaker, remote controlled switch, auto reclosers etc. has been presented by the researcher to enhance the system performance. Apart from this optimal placement of distributed generation (DG), reconfiguration is also the proven technique to improve the system reliability. The optimal placement of DG and switches can be obtained using the various metaheuristic algorithm as suggested by so many researchers. But here author want to relate the reliability of the system with switches failure conditions. Although a very few authors have considered the effect of switch failure to calculate the reliability.

1.1 Motivation

This research is motivated by the fact that there is a growing demand to have highly reliable power supply and the rising pressure on distribution utilities to enhance the continuity of their services as well as the operational costs. Because the distribution network is the most vulnerable part of the power system, even slight error in the modelling of reliability can cause serious shifts in the results of the performance evaluation and planning.

Protective devices do not necessarily perform as planned in the real-world distribution system and when they fail, they can bring about extensive outages and lengthy periods of restorative processes. The effect of such failures is however not given much attention in the reliability-based planning research. The current study can be driven by the fact that there is a need to close the gap between theoretical reliability models and a real network behaviour through the introduction of the switch failure probability into the reliability assessments and optimisation procedure. In this way, this study is expected to equip the utility engineers and planners with a more realistic and sounder decision-making instrument to use in deploying switches in radial distribution networks.

2 Reliability Indices

Several research has been done to determine the reliability effect. Typically, reliability measurements are separated into two categories: Customer focused and load focused indices. Variables such as outage durations, failure rates, load magnitude and client count are included in these measurements. In this study we use reliability indices such as SAIDI, SAIFI, CAIDI, ASAI, and ENS[1-2]. The distribution system consists of a number of interrelated components which transmit electrical power from the transmission system to end use consumers. These are the elements comprising feeders, distributors, service mains among others. To keep consumers' power supplies steady, all of these components have to work correctly. Any one of these series components can malfunction or suffer any disturbance and result in power outages or interruptions. The three basic reliability parameters of average failure rate (λ_s), average outage duration (r_s), and average annual outage (U_s) time are given by[1-2],

$$\lambda_s = \sum_t \lambda_t \quad \ldots (1)$$

$$U_s = \sum_t \lambda_t . r_t \quad \ldots (2)$$

$$r_s = \frac{U_s}{\lambda_s} = \frac{\sum_t \lambda_t r_t}{\sum_t \lambda_t} \quad \ldots (3)$$

2.1 System Average Interruption Frequency Index (SAIFI)

$$SAIFI = \frac{\sum \lambda_t M_t}{\sum M_t} \quad \ldots (4)$$

where λ_t is the failure rate and M_t is the total consumers connected to load point t.

Table 1 — Historical Literature survey

Ref.	Design Variable	Electrical Device	Techniques	Remarks
[31]	Location and Number	Isolators	GA	Not consider failure probability of devices
[30]	Reconfiguration	NA	GA & PSO	Reconfiguration of distribution network
[27]	Location and size	Sectionalizing switches (SS)	GA	Considering failure probability SS
[28]	Location	SS	MIP	Consider switch failure
[29]	Location, type, number	Automatic switch (AS)/ Protection device (PD)	PSO, GA	Effect of malfunction on SS and protection device
[24]	Location	DG	GA	Not consider
[23]	Location number	Switch	PSO	Switch failure considers
[22]	Location number	DG, SS	MILP	Failure probability of switch did not consider.
[20]	location	DG	MCS	Time consuming, load growth is not consider.
[19]	sizing	DG	PSO	Reliability, protection and security did not consider
[18]	Size, location	DG	Analytical approach	Switch failure probability not consider.
[17]	location	Automatic Switch	Algebraic approach	Switch failure probability not consider.
[16]	Location	DG	Harmony search	Switch failure probability not consider.
[15]	Location	DG	Evolutionary Programming	Various DG can be implemented
[14]	Location, Number	Switch	GA	Failure probability not consider

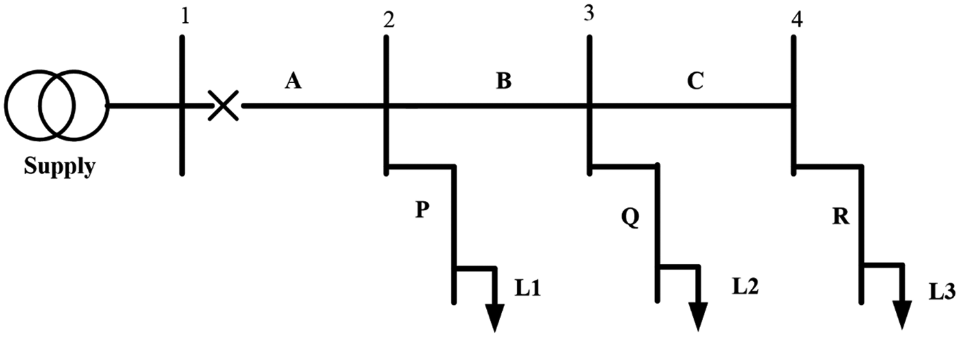

Fig. 1 — Radial distribution network of 4 bus system

2.2 System Average Interruption Duration Index (SAIDI)

$$SAIDI = \frac{\Sigma\, U_t M_t}{\Sigma\, M_t} \quad \dots (5)$$

where U_t is average yearly outage duration of load point t.

2.3 Customer Average Interruption Duration Index (CAIDI)

$$CAIDI = \frac{SAIDI}{SAIFI} \quad \dots (6)$$

2.4 Average Service Unavailability Index (ASUI)

$$ASAI = \frac{\sum_t U_t M_t}{\sum_t M_t \times 8760} \quad \dots (7)$$

2.5 Energy Not Served (ENS)

Total energy not supplied by the system

$$ENS = \sum U_t \times W_t \quad \dots (8)$$

where, W_t is the average load connected to load point t.

3 Literature Review

The existing literature on various techniques, methodology and optimization used to enhance the distribution system reliability which has been proposed by different scholars is shown in Table 1.

4 Research Methodology

Consider a single line diagram of a typical radial distribution network as shown in Fig. 1 having one

Table 2 — Reliability parameters for 4 bus radial distribution network (Fig. 1)

Components	Length (km)	Failure rate(fl/year) λ	r Repair time (hr)
Segment			
A	1	0.12	3
B	2	0.24	3
C	2	0.24	3
Distributors			
P	2	0.48	2
Q	2	0.48	2
R	3	0.72	2

Table 3 — Reliability indices for the system of Fig. 1

Components failure	L1 (load point)			L2 (load point)			L3 (load point		
Segment	λ(fl/yr)	r	U	λ(fl/yr)	r	U	λ(fl/yr)	r	U
A	0.12	3	0.36	0.12	3	0.36	0.12	3	0.36
B	0.24	3	0.72	0.24	3	0.72	0.24	3	0.72
C	0.24	3	0.72	0.24	3	0.72	0.24	3	0.72
Distributors									
P	0.48	2	0.96	0.48	2	0.96	0.48	2	0.96
Q	0.48	2	0.96	0.48	2	0.96	0.48	2	0.96
R	0.72	2	1.44	0.72	2	1.44	0.72	2	1.44
Total	2.28	2.26	5.16	2.28	2.26	5.16	2.28	2.26	5.16

feeder and three distributors connected with some load points. For Fig. 1, let us assume the main segments A, B, C have a failure rate of 0.12 and the lateral distributors P, Q, R have a failure rate of 0.24. The reliability parameters for above system are shown below in Table 2. Typically, power in a distribution system flows from a substation to end-users through feeders, distribution transformers, distributors, and service mains. If any component failures effect in short circuits, each failure will trigger the operation of the source circuit breaker. Since there are no any isolators in the system, hence every failure must be repaired to resume the power supply to the consumers. Based on explained operational technique, the reliability indices for each load point (L1, L2, L3) can be calculated using the principles of series systems, as described in Eqs. (1-3) illustrated in Table 3.

From Table 3, the basic indices of the above system are same. Therefore, it is claimed that the operating strategy for this type of arrangement is not very accurate and therefore some advance features such as transferable loads, advance protection and isolation can be comprised. Let us assume the number of consumers connected to load points L1, L2, L3 and their average load demands be shown in Table 4. Then we can calculate the other indices using Eqs. (4-8).

The other indices evaluated for the system shown in Fig. 1 are as follows,

Table 4 — Load data

Load points	No of consumers	Load demand(kW)
L1	1200	4000
L2	1000	3800
L3	800	3200

SAIFI = 2.28
SAIDI= 5.16
CAIDI=2.26
ASUI= 0.00058
ENS=56.76

4.1 Effect of Fuse in Distributor Protection

Now consider the system shown in Fig. 2, this is very practical distribution system frequently used by distribution company. In the above arrangement there is one source circuit breaker (CB), two isolators in main segment of lines B, C, and three distributors P, Q, R connected with fuse to provide the reliable power supply. The above arrangement is very practical, often seen whenever we look any public distribution network. In this situation, any fault short on a lateral distributor consequence in the blowing of its corresponding fuse, disconnecting the connected load point until the fault is refurbished. However, this does not impact to any other load points.

Therefore, the reliability indices for each load point (L1, L2, L3) can be calculated using the concepts

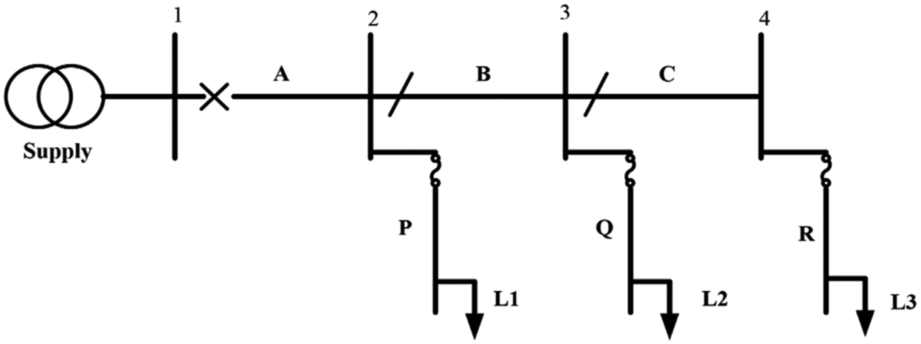

Fig. 2 — Radial distribution network with fuse and isolators

Table 5 — Reliability indices for the system of Fig. 2 (considering fuse only)

Components failure	L1 (load point)			L2 (load point)			L3 (load point		
Segment	λ(fl/yr)	r	U	λ(fl/yr)	r	U	λ(fl/yr)	r	U
A	0.12	3	0.36	0.12	3	0.36	0.12	3	0.36
B	0.24	3	0.72	0.24	3	0.72	0.24	3	0.72
C	0.24	3	0.72	0.24	3	0.72	0.24	3	0.72
Distributors									
P	0.48	2	0.96						
Q				0.48	2	0.96			
R							0.72	2	1.44
Total	1.08	2.55	2.76	1.08	2.55	2.76	1.32	2.45	3.24

explained earlier, illustrated in Table 5 Also, the additional indices can be evaluated using Table 5.

In this scenario, all load points experience an improvement in their reliability indices, although the extent of enhancement varies among them. Load point L3 remains the least reliable, primarily due to the comparatively higher failure rate associated with its lateral distributor. Frequent faults occurring in lateral distributor R significantly influence the reliability performance of L3, making it more susceptible to interruptions than the other load points. The supplementary reliability indices for this network are as follows,

SAIFI = 1.144
SAIDI= 2.888
CAIDI=2.52
ASUI= 0.00032
ENS=31.896

4.2 Effect of Isolators and Fuse

The system shown in Fig. 2 having isolators as well as fuse for protection of lines and supply reliable power to the clients. If any fault happens in the feeder, then the source CB will operate and power supply will be discontinued till fault is cleared. Then nearest isolator will operate and faulty segment will be separated so that system can supply upto a marginal load till fault is not cleared. But if fault occurs in any distributors (P. Q, R) then fuse will glow and distributors will separate from main feeder so that power supply will continue to full segments (A, B, C or any distributor P, Q, R which is not faulted). Here we are assuming that isolator or fuse is in ideal i.e. their failure probability is 0. But whenever any fault occurs in main section then end node consumers will heavily affect. Let us assume the total isolation and switching time be 0.4 hour.

Therefore, the reliability indices for each load point (L1, L2, L3) can be calculated using the principles of series systems, illustrated in Table 6.

Here, load points L1 and L2 reliability indices have improved and it is observed that the improvement is larger for those that are closer to the supply point and smaller for those that are farther away. Since the isolator cannot eliminate the impact of any failure on load point L3, its indices stay the same. The supplementary reliability indices for this network are as follows,

SAIFI = 1.144
SAIDI= 2.1808
CAIDI=1.906
ASUI= 0.00025
ENS= 24.5328

The effect of only isolators in distribution network has been discussed without considering isolator

Table 6 — Reliability indices for the system of Fig. 2 assuming fuse and isolator

Components failure	L1 (load point)			L2 (load point)			L3 (load point		
Segment	λ(fl/yr)	r	U	λ(fl/yr)	r	U	λ(fl/yr)	r	U
A	0.12	3	0.36	0.12	3	0.36	0.12	3	0.36
B	0.24	0.4	0.096	0.24	3	0.72	0.24	3	0.72
C	0.24	0.4	0.096	0.24	0.4	0.096	0.24	3	0.72
Distributors									
P	0.48	2	0.96						
Q				0.48	2	0.96			
R							0.72	2	1.44
Total	1.08	1.4	1.512	1.08	1.978	2.136	1.32	2.45	3.24

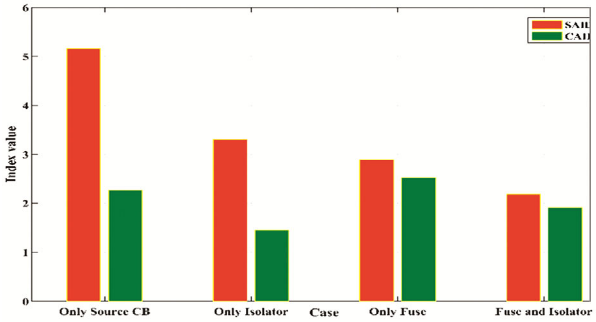

Fig. 3 — Comparison of SAIDI and CAIDI

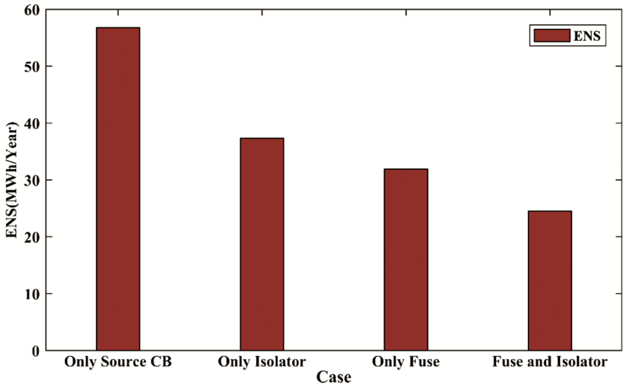

Fig. 4 — Comparison of ENS

individually. The data from Table 3 has been taken for evaluating the additional indices which is as follows,

SAIFI = 2.28
SAIDI= 3.3008
CAIDI=1.447
ASUI= 0.00037
ENS= 37.3392

As per distribution network is concern, it has been discussed and analysed that how the placement of protection devices such as CB, isolators, fuse impact the reliability indices. Figure 3 shows that the isolator and fuse together reduce the reliability indices SAIDI and CAIDI significantly as well Fig. 4 also confirms that ENS goes down with the combination of both protective devices. But, so far, our protective devices are ideal as supposed to be operate in abnormal situation. Now if protective devices fail to operate then how the reliability indices affect.

4.3 Effect of Protective Device Failures

In the above sections, the reliability indices were determined considering that the fuses in the distributor are supposed to operate whenever any fault occurs on the distributor to which they are connected. There are some circumstances when the primary protection system will not be able to work as it was designed. In such cases the backup protection system is supposed to be activated which will further maintain the operational safety and reliability of the system. In order to analyse the effect of failure of protective device is shown in Fig. 2, we assume that the fuse operates with a probability of 0.9, i.e. the fuses operate successfully 9 time out of 10 when required. The influence to the failure rate can be assessed using the concept of expectation.

$$failure\ rate = (failure\ rate|fuse\ operates) \times p + (failure\ rate\ |fuse\ fails) \times q \quad \ldots (9)$$

where, p = probability of fuse to be operate successfully

q = probability of fuse fails= 1-p

$$\lambda_{90\%\ probability} = 0 \times 0.9 + \lambda_{device} \times 0.1 \quad \ldots (10)$$

Under these conditions, the failures on distributions P, Q, and R also added to the indices of load point L1. In the same manner, failure rate contributions for load point L2 and L3 can be computed using expectation.

Therefore, the contribution to the failure rate of load point L1 by distributor Q is calculated as

$$failure\ rate = 0 \times 0.9 + 0.48 \times 0.1 = 0.048$$

Similarly, the contribution to the failure rate of load point L1 by R is calculated as,

$$failure\ rate = 0 \times 0.9 + 0.72 \times 0.1 = 0.072$$

Table 7 — Considering fuse operation probability 0.9

Components failure	L1 (load point)			L2 (load point)			L3 (load point		
Segment	λ(fl/yr)	r	U	λ(fl/yr)	r	U	λ(fl/yr)	r	U
A	0.12	3	0.36	0.12	3	0.36	0.12	3	0.36
B	0.24	0.4	0.096	0.24	3	0.72	0.24	3	0.72
C	0.24	0.4	0.096	0.24	0.4	0.096	0.24	3	0.72
Distributors									
P	0.48	2	0.96	0.048	0.4	0.0192	0.048	0.4	0.0192
Q	0.048	0.4	0.0192	0.48	2	0.96	0.048	0.4	0.0192
R	0.072	0.4	0.0288	0.072	0.4	0.0288	0.72	2	1.44
Total	1.2	1.3	1.56	1.2	1.82	2.184	1.416	2.31	3.2784

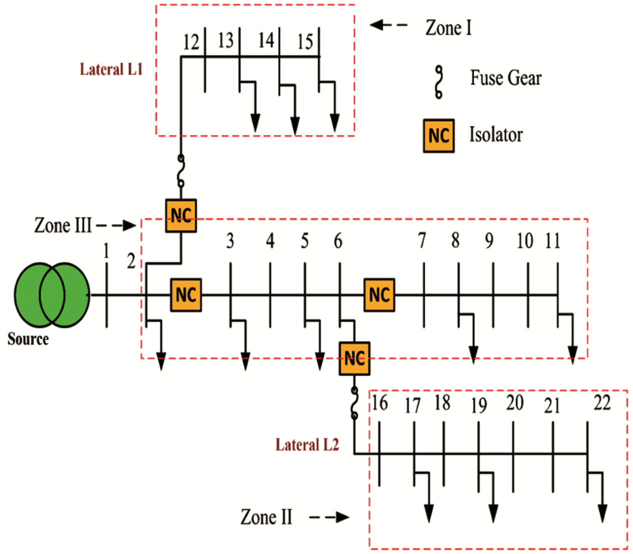

Fig. 5 — Modified 22 bus radial distribution system

Let us assume the total isolation and switching time be 0.4 hour. Therefore, the reliability indices for each load point (L1, L2, L3) can be calculated using the concept of exception, illustrated in Table 7.

When the fuse functions correctly 90 % of the time, the reliability indices of the system reflect the combined effect of successful fuse operation and the remaining 10 % chance of fuse maloperation. A correctly operating fuse isolates the faulted lateral and prevents upstream interruptions, leading to reduced customer outages. However, if the fuse fails to operate, the fault affects a larger section of the network and increases the number of customers interrupted, which in turn affects indices such as SAIFI, SAIDI, CAIDI, and ENS. Thus, the overall reliability indices are computed by considering both scenarios successful fuse operation and fuse failure weighted according to their respective probabilities.

The results presented in Table 7 demonstrate that the reliability of each load point decreases as anticipated. The degree of this degradation is influenced by two main factors the probability of the fuse operating successfully and the relative impact of the additional failure events in comparison to those that occur even when the fuses are assumed to be 100 % reliable in their operation. i.e. the effect of failure of one element influences other. The additional indices can be evaluated as,

SAIFI = 1.2576
SAIDI= 2.1049
CAIDI=1.6737
ASUI= 0.00024
ENS= 25.03

5 Problem Formulation

Switches help lower the duration of customer outages, which in turn reduces the cost associated with service interruptions. However, installing these switches adds equipment expenses to the system. Thus, an appropriate balance between interruption costs and equipment costs is needed to determine the best placement strategy. The goal of the proposed model is to minimize the overall cost of the system; the objective function of this problem can be expressed as

$$Minimize\ (\ C_{eqp} + C_{intrup}\ ) \qquad \ldots (11)$$

$$C_{eqp} = \sum_{m\in N} I_m^{RCS} Y_m^{RCS} + I_m^{isolator} Y_m^{isolator} \qquad \ldots (12)$$

$$C_{interp} = \sum_{p\in N} \sum_{q\in N} \lambda_p C_{p,q} \qquad \ldots (13)$$

where, Y_m^{RCS} and $Y_m^{isolator}$ indicate binary variable related with remote controlled switch (RCS) and Isolator switch. $I_m^{isolator}$ and I_m^{RCS} indicates the investment cost of isolators and RCS respectively. λ_p is the failure rate of segment p in the feeder is shown in Fig. 5.

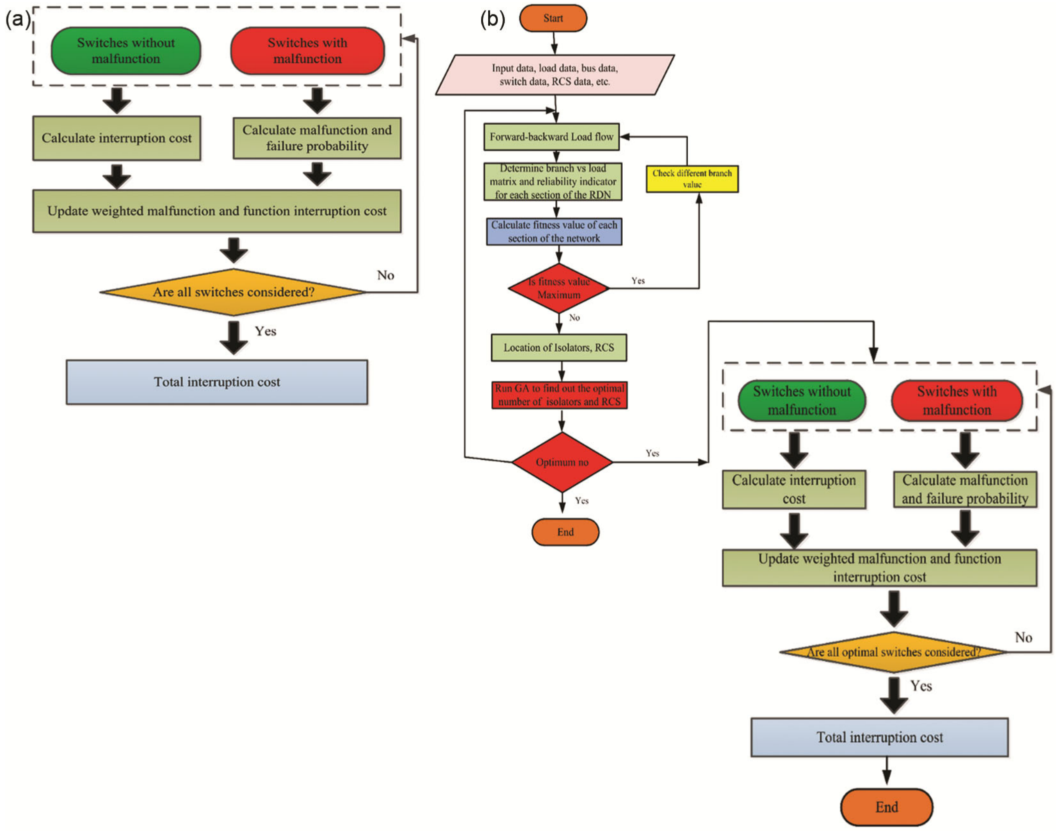

Fig. 6 — (a) Flowchart to calculate total interruption cost considering switch failure probability; (b) flowchart of the proposed algorithm

$C_{p,q}$ denotes the interruption cost at load point (q) when a fault occurs in section (p). This cost varies based on how switches are arranged within the distribution network. As a result, the effect of switch placement and operation on feeder performance is reflected through the value of $C_{p,q}$.

Depending on how the switches are arranged in the feeder, customers can be restored through three different methods: restoration using RCS, restoration using an isolator, or restoration only after the faulty section has been repaired. Since switches were assumed to operate without failure. In reality, switches, like any other system component, can also malfunction. These failures can be treated similarly to feeder section failures, but since the exact locations of the switches are not known beforehand, their failure effects cannot be assigned directly to feeder sections. Therefore, a model is needed that incorporates switch failures at the same time the switches are being placed in the network. This allows the optimization process to account for the reliability of both RCSs and Isolators. To properly reflect the impact of switch failures on system performance, additional interruption cost terms must be included in the objective function. These added costs represent the extra outages customers may experience when a switch fails, ensuring the model captures the true reliability implications of installing RCSs and isolators.

$$RCS\ failure\ interruption\ cost = \sum_{p\in N}\sum_{q\in N}\lambda_p^{RCS}C_{p,q}^{RCS} \quad \dots (14)$$

$$Isolator\ failure\ interruption\ cost = \sum_{p\in N}\sum_{q\in N}\lambda_p^{Isolator}C_{p,q}^{Isolator} \quad \dots (15)$$

$C_{p,q}^{Isolator}$ and $C_{p,q}^{RCS}$ indicate consumer interruption cost linked with Isolator failure and RCS failure. Whereas $\lambda_p^{Isolator}$ and λ_p^{RCS} are the failure rates of isolators and RCS.

Therefore, the final objective function can be expressed as

$$Minimize\ \left(\sum_{m\in N}I_m^{RCS}Y_m^{RCS} + I_m^{isolator}Y_m^{isolator} + \sum_{p\in N}\sum_{q\in N}\lambda_p^{RCS}C_{p,q}^{RCS} + \sum_{p\in N}\sum_{q\in N}\lambda_p^{Isolator}C_{p,q}^{Isolator}\right) \quad \dots (16)$$

The Fig. 6 (a) shows the flowchart to calculate the total interruption cost taking all conditions in account.

The optimal location of RCS and isolators can be obtained using GA as explain[31]. The Fig. 6 (b) shows the proposed algorithm to determine the optimal location of switches (isolators, RCS) and also calculate the interruption costs.

5.1 Key Benefits of the Proposed Algorithm

The proposed reliability-oriented planning technique offers several practical and technical benefits for radial distribution networks.

5.1.1 Realistic reliability assessment

The proposed technique explicitly incorporates the failure probability of protective devices, providing a more accurate and practical estimation of reliability indices compared to conventional models that assume ideal switch operation.

5.1.2 Economically Optimal Planning

By simultaneously minimizing investment cost, customer interruption cost, and additional outage cost due to switch failures, the method ensures a balanced and cost-effective switch placement strategy.

5.1.3 Avoidance of over installation

The approach identifies the optimal number of protective devices beyond which reliability improvement becomes marginal, preventing unnecessary installation of isolators and RCS units.

5.1.4 Improved decision-making for utilities

The framework helps distribution utilities understand the true impact of protective device maloperation on system performance, supporting more informed and robust planning decisions.

5.1.5 Scalability and applicability

The GA-based optimization framework is computationally efficient and scalable, making it suitable for practical, large-scale radial distribution networks with varying reliability and cost parameters.

6 Results and Discussion

The proposed method is tested on a modified o IEEE 34-bus system of distribution network. To analyze, the cost of investment of the is isolators and RCS units are assumed to be 680 and 4800 dollars respectively. The whole algorithm has been developed in MATLAB 2016 and executed on a dual-core 3200 MHz, 8 GB, a 64-bit operating system on a PC. The restoration times utilized in the study are 4 minutes to operate RCS, 1.2 hours to isolators and 4 hours to repair components. Isolators and RCS devices both have a failure rate of 0.01 each year. Total number of consumers connected is 2053 and load demand 8.937 MW. The isolation time and tariff rate for this problem are 0.6 hours and 8.0, respectively. To solve the optimization problem using GA, a population size of 100 and 50 iterations has been used and run time for the algorithm is 45 sec.

In order to analyze the efficiency of the approach, three situations are taken into consideration

(i) Positioning of isolators only,

(ii) Installation of RCS equipment exclusively, and

(iii) Joint isolation of the two as well as RCS.

The failure mode of each scenario is evaluated with and without considering the chance of switch failure. The respective findings are summarized as Tables 8 and 9.

Based on the results presented in Tables 8 and 9, Case I shows that when the failure of isolators is taken into account, the optimal number of isolators decreases from 17 to 10. Similarly, in Case II, considering the possibility of RCS failure reduces the number of selected RCS units from 9 to 7. This indicates that incorporating switch failure into the

Table 8 — Output considering switches without failure

Cases	Number		Cost			Reliability index
	Isolators	RCS	Equipment cost	Interruption cost	Total	SAIDI (p.u.)
Case 1	17	……	11560	49140	60700	0.5439
Case 2		9	43200	15356	58556	0.5245
Case 3	12	5	32160	12285	44445	0.5138

Table 9 — Output considering switches failure

Cases	Number		Cost ($)			Reliability index
	Isolators	RCS	Equipment cost ($)	Interruption cost ($)	Total Cost ($)	SAIDI (p.u.)
Case 1	10	……	6800	73710	80510	0.685
Case 2		7	33600	39926	73526	0.578
Case 3	11	5	31480	36855	68335	0.587

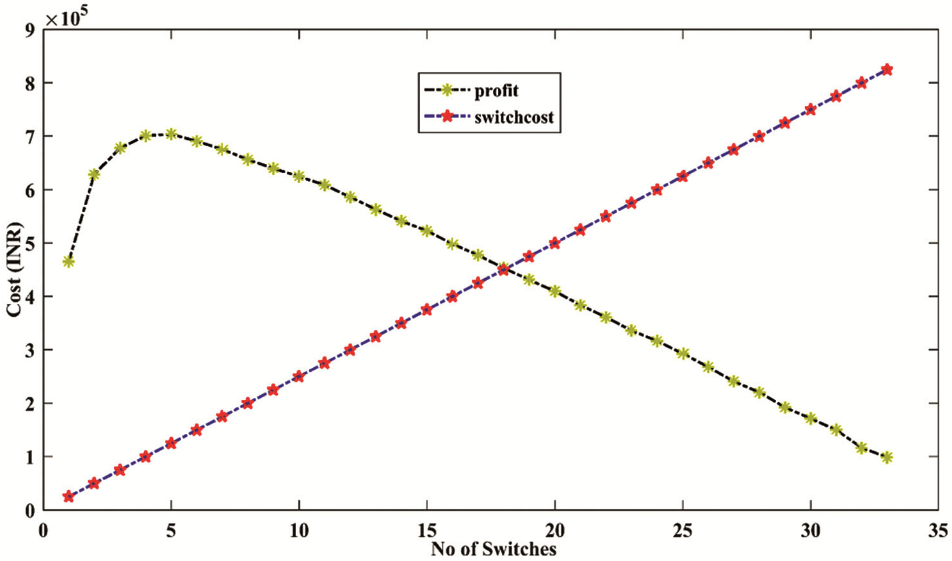

Fig. 7 — Plot of switch cost and profit

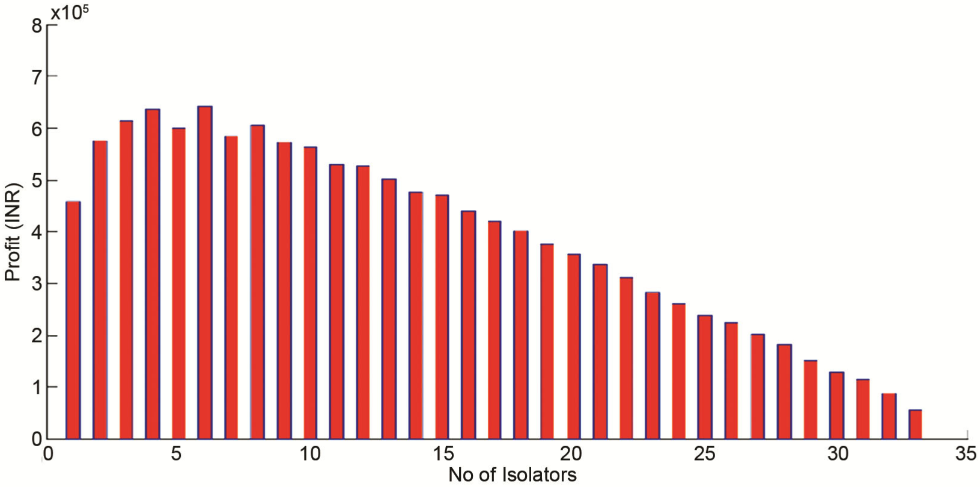

Fig. 8 — Utilities profit

planning process reduces the overall benefit of these devices, leading to fewer switches being installed. Moreover, for both cases, accounting for switch failure results in higher SAIDI values. The increase in SAIDI occurs because failed switches contribute additional interruptions to the system. The rise in SAIDI is influenced not only by these added interruptions but also by the reduction in the number of switches installed, which limits the system's ability to isolate faults quickly. In Case III, although the total number of installed switches remains nearly the same, the reliability indices still show significant deterioration. This is primarily due to the negative impact of switch failures, which generate extra outages across the network. Overall, the findings highlight that ignoring switch failure leads to an overestimation of their effectiveness and may result in unrealistically optimistic predictions of system reliability and performance.

Figure 7 shows the variation of switch cost and profit and it is observed that the optimum number of protective devices required for 34 bus systems is 17. The profit shown in Fig. 8 was also enhanced as well and we also detected the after 17 buses profit went down but ENS or SAIDI did not improve significantly.

Figure 9 shows the effect of failure probability of protective devices and it is observed that if any protective devices fail then system reliability goes down. The system SAIDI after optimal placement of 17 protective devices in the radial distribution system assuming 100 % reliable switch is 13.94 but if 90 % reliable switch then the system SAIDI is 14.36.

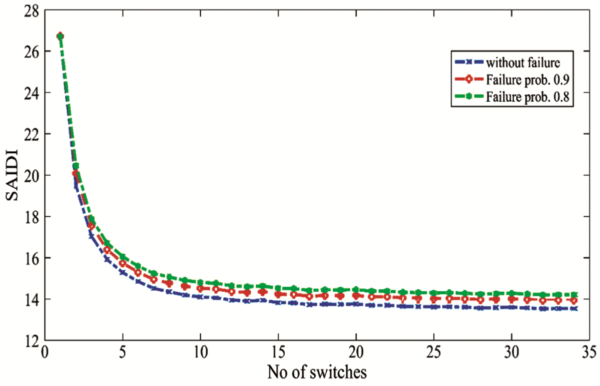

Fig. 9 — Variation of SAIDI

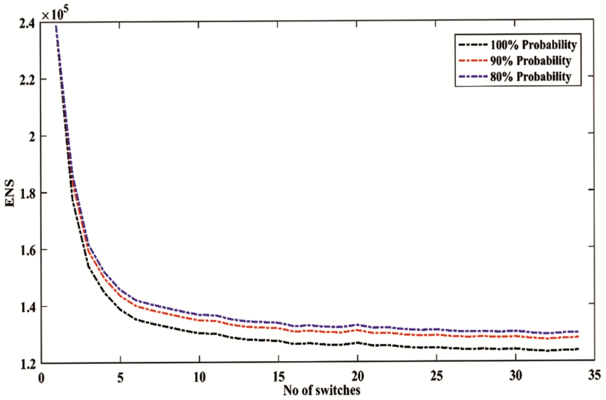

Fig. 10 — Variation of ENS

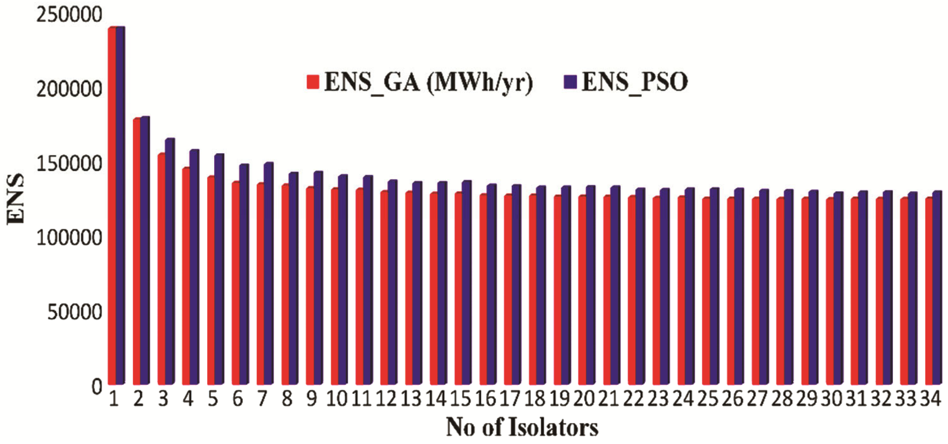

Fig. 11 — Comparison of ENS (GA & PSO)

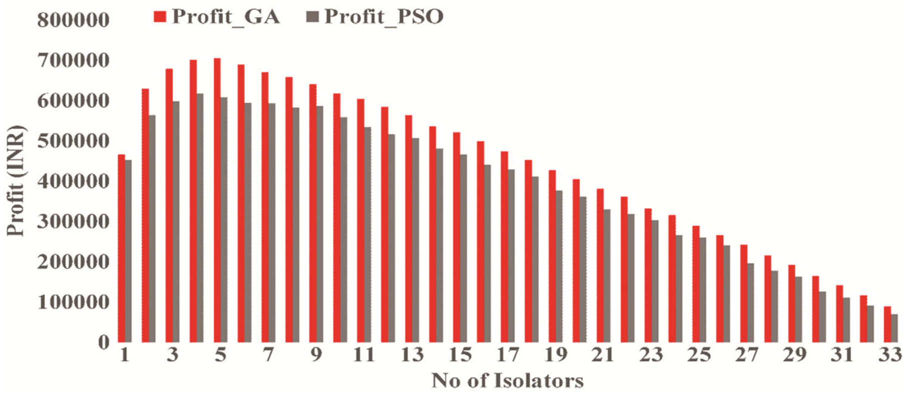

Fig. 12 — Comparison of Profit (GA & PSO)

Figure 10 shows the variation of ENS considering 100 % to 80 % reliable protective devices. It is observed that the system ENS for 100 % reliable switch is 126.54 MWh and for 90 % reliable switch ENS is 130.97 MWh.

6.1 Comparative Analysis

A comparative study is carried out using Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) on the 34-bus distribution system. The results indicate that, although both methods improve system performance, the GA-based approach consistently achieves superior solutions in terms of reliability enhancement and cost optimization compared to PSO. Figures 11 and 12 shows that the proposed method provides best ENS and profit to the utilities. Table 10 shows the benefits of proposed work. From the Table 10 shows the proposed work has

Table 10 — Comparison of proposed work

	No of Isolators	No of RCS	Equipment cost	Total cost
Ref [27]	18	9	51300	216900
Proposed method	11	5	31480	68335

significant benefits in terms of cost as well as number of required switches.

7 Conclusion

The effect of protective devices and failure probability of protective devices on the reliability of a radial distribution system has been analysed. It was observed in the analysis that the distribution network is the most vulnerable component of the power system and requires close planning so as to provide reliable and cost-effective services to the consumers. Through the comparison of a 4-bus system and a modified IEEE 34-bus system, it was demonstrated that the lack of protective devices leads to the general outages, since all faults block the supply to all points of loads. The addition of fuses and isolators contributed greatly to the increase of reliability through selective isolation and prompt restoration.

Nevertheless, the research also showed that real-life appliances are not flawless. Reliability indices like SAIDI and ENS worsened when the probability of failure of fuses and switches were factored into consideration which underlines the fact that even minimal changes towards a negative impact of the dependability of devices on the overall system behavior. To solve this, a GA-based optimization model was formulated to determine the optimal places where remote-controlled switches and isolators should be situated considering the effects of functionality and equipment breakdowns. The experiment of optimization showed that installing 17 protective devices was the most appropriate balance between cost, reliability gain, and utility profit, and there is no significant gain after that point.

Despite the fact that the current study represents an elaborate reliability analysis that takes into account the failure of the protective devices and the optimal location of the switch, a number of extensions can be pursued in further research. It is possible to extend the proposed framework to incorporate other protective equipment like reclosers and circuit breakers that have varying failure properties. In addition, failure rates that change with time based on aging, maintenance strategies and environmental conditions can be included to increase the accuracy of the models.

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