

Optimal Recloser Placement in Rural and Urban 11 kV Distribution Feeders of Nepal Based on Reliability and Cost–Benefit Analysis

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Abstract

Reliability improvement of distribution systems is a major concern for utilities in Nepal due to frequent interruptions in both rural and urban feeders. This study investigates the optimal placement of auto-reclosers in two practical 11 kV feeders: Feeder-4 (urban) under the Birgunj Distribution Center and the Khoplang feeder (rural) under the Gorkha Distribution Center. Base-case reliability indices (SAIFI, SAIDI, CAIDI, and EENS) were evaluated using analytical modeling and ETAP simulation. A Genetic Algorithm (GA)-based optimization framework was developed to minimize Expected Energy Not Supplied (EENS) and maximize economic benefits. The results indicate that 2 reclosers are optimal for the Feeder-4 (urban) feeder and 4 recloser for the Khoplang (rural) feeder. SAIDI and EENS were reduced by more than 55% in both feeders. Cost–benefit analysis yielded benefit–cost ratios greater than 2.0 and payback periods of less than four years, confirming economic feasibility.

Keywords—Distribution reliability, Auto-recloser, Genetic Algorithm, SAIDI, EENS, Cost–benefit analysis

1. INTRODUCTION

The electric power system is broadly divided into generation, transmission, distribution, and load subsystems. Among these, the distribution system has the most direct interaction with end consumers and therefore has the greatest influence on customer satisfaction and utility performance. Studies indicate that nearly 80% of customer interruptions in power systems originate from the distribution network[1]. This highlights the critical importance of improving distribution system reliability.

In Nepal, distribution feeders—particularly 11 kV radial feeders—are frequently subjected to interruptions due to long feeder lengths, exposure to adverse weather conditions, vegetation encroachment, aging infrastructure, and limited automation. Rural feeders are typically characterized by extended radial structures and low load density, making them more vulnerable to sustained outages. In contrast, urban feeders have shorter lengths and higher load density but experience seasonal overloading and fault incidents. Reliability

indices such as System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), and Expected Energy Not Supplied (EENS) are widely used to quantify the performance of distribution systems [1], [2].

Overhead distribution systems are particularly susceptible to temporary faults caused by lightning, wind, tree contact, and animal interference. Research shows that approximately 70– 90% of faults in overhead distribution systems are temporary in nature [7]. Auto-reclosers (ACRs) are effective protective devices capable of automatically interrupting fault current and reclosing the circuit to restore supply if the fault is transient. Proper installation of reclosers significantly reduces interruption duration and limits the number of customers affected during fault events [6], [10].

Motivated by these gaps, this research investigates the optimal placement of auto-reclosers in two practical 11 kV feeders of Nepal: Feeder-4 (urban) under Birgunj Distribution Center and Khoplang feeder (rural) under Gorkha Distribution Center. The study integrates analytical reliability modeling, ETAP-based system representation, and Genetic Algorithm optimization to minimize EENS and maximize economic benefit. A comprehensive cost–benefit analysis is performed to evaluate the financial feasibility of the proposed solution.

2. LITERATURE REVIEW

Reliability evaluation of distribution systems has been extensively studied due to its direct impact on customer satisfaction and utility performance. Billinton and Allan [1] established the fundamental analytical framework for power system reliability evaluation and introduced standard indices such as SAIFI, SAIDI, CAIDI, and Expected Energy Not Supplied (EENS). These indices remain widely adopted for distribution planning and operational assessment. The Roy Billinton Test System (RBTS) has frequently been used as a benchmark for validating analytical and simulation-based reliability methods [2].

Distribution feeders, particularly overhead radial systems, are highly susceptible to environmental disturbances. Horton and Goldberg [4] reported that a significant portion of sustained outages in overhead distribution systems is caused by external factors such as weather and vegetation. Auto-reclosers have therefore become essential protection devices in distribution networks, as they can clear temporary faults and restore supply automatically. Studies have shown that appropriate recloser installation significantly reduces interruption duration and limits the number of affected customers [6], [7].

Optimal placement of protective devices is a combinatorial optimization problem. Various metaheuristic techniques, including Particle Swarm Optimization (PSO) and Genetic Algorithm (GA), have been applied for sectionalizing switch and recloser placement in radial distribution systems [12], [13]. These methods effectively handle nonlinear objective functions and discrete decision variables. Dhole et al. [16] further integrated reliability improvement with cost–benefit analysis and demonstrated that optimal recloser placement

can achieve benefit– cost ratios greater than unity, ensuring economic feasibility.

Despite these contributions, most studies are conducted on standard test systems or under generalized assumptions. Comparative analysis between rural and urban feeders using real utility data, particularly in the Nepalese context, remains limited. Therefore, this study focuses on practical 11 kV rural and urban feeders of Nepal and integrates analytical reliability modeling with GA-based optimization and economic evaluation.

3. METHODOLOGY

The methodology adopted in this study integrates distribution system modeling, reliability evaluation, Genetic Algorithm (GA)-based optimization, and cost–benefit analysis to determine the optimal placement of auto-reclosers in rural and urban feeders.

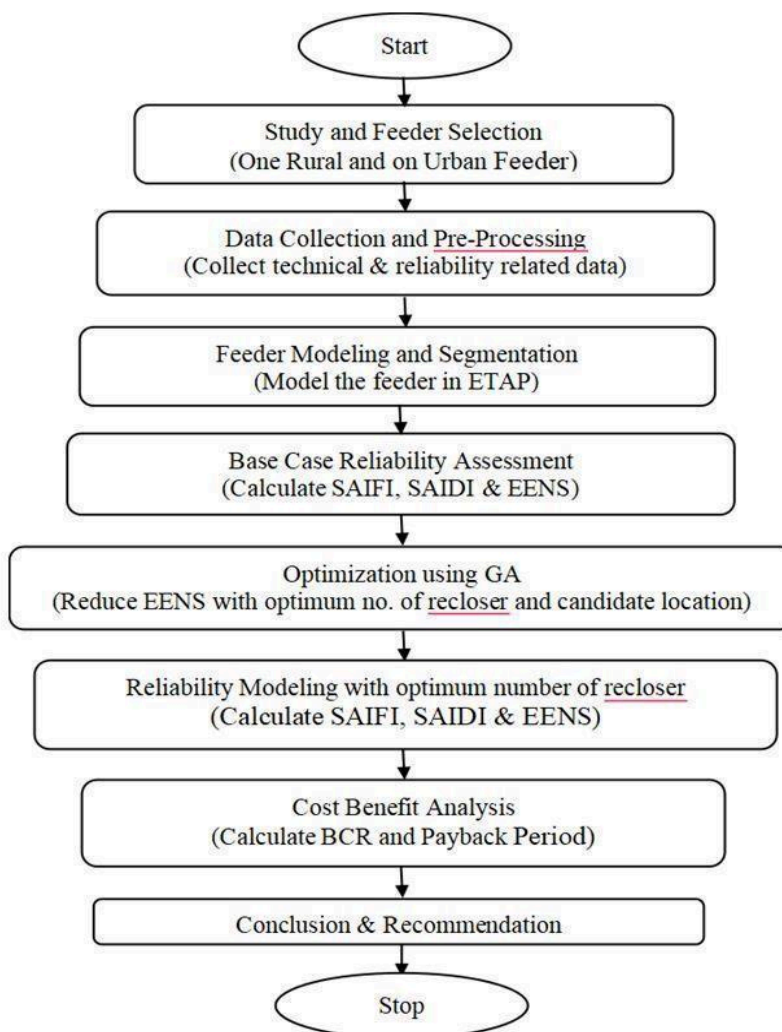


Figure 1: Flow chart of methodology

Two practical 11 kV radial feeders were selected: Feeder-4 (28 km urban feeder) under the Birgunj Distribution Center and the Khoplang feeder (114 km rural feeder) under the Gorkha Distribution Center. A three-year historical outage dataset (2022–2024) was collected from Nepal Electricity Authority (NEA) distribution centers.

Faults were classified based on outage duration and system restoration behavior. Faults with durations less than 5 minutes were classified as temporary faults (typically cleared automatically by reclosers), whereas faults with durations greater than 5 minutes were classified as permanent faults, requiring manual repair and isolation.

The study applies analytical reliability evaluation techniques supported by statistical estimation:

$$\text{Failure Rate Estimation } (\lambda) = \frac{\text{Total number of outages}}{\text{Total observation period (years)}}$$

$$\text{Mean Time to Repair (MTTR)} = \frac{\sum \text{Outage durations}}{\text{Number of outages}}$$

Standard indices such as SAIFI, SAIDI, CAIDI, and EENS are computed using deterministic analytical formulas based on extracted λ and r values.

These reliability parameters were used to compute base-case reliability indices, including SAIFI, SAIDI, CAIDI, and Expected Energy Not Supplied (EENS), using analytical reliability modeling. The feeders were modeled in ETAP to validate network topology, load distribution, and protection configuration.

The objective function was formulated to maximize net economic benefit, defined as;

$$\text{Maximize profit } f(x) = B(x) - C(x)$$

Where;

$B(x)$ = Total economic benefit due to reliability improvement

$C(x)$ = Total cost of recloser installation and maintenance

Here, the decision variables are;

$$x_i = \begin{cases} 1, & \text{if a recloser is installed at section } i \\ 0, & \text{otherwise} \end{cases}$$

$$x = [x_1, x_2, \dots, x_N]$$

Where,

N = total number of candidate feeder sections

x_i = binary decision variable

Further;

Benefit function $B(x) = \{EENS_{base} - EENS(x)\}xVOLL$
 (base case EENS - EENS after recloser placement) x Value
 of lost load

$$Cost\ function\ C(x) = \sum_{i=1}^N xi(Ccap + Cinst) + Cmaint$$

Where,

Ccap = Capital cost of one recloser Cinst = Installation cost

Cinst = Installation cost

Cmaint = Total maintenance cost over lifecycle

Constraints;

$$1. \text{ Maximum number of recloser } \sum_{i=1}^N xi \leq Nmax$$

Where N_{max} = Maximum allowable number of reclosers

2. The feeder must remain radial

3. To maintain coordination between protective devices; $T_{upstream} > T_{downstream} + \Delta T$

Where;

$T_{upstream}$ = Operating time of upstream device

$T_{downstream}$ = Operating time of downstream device

ΔT = Coordination time margin

The formulation is based on following assumptions;

- Failure events follow a Poisson process (constant failure rate)
- Repair times follow an exponential distribution.
- Load demand is assumed constant during outage periods.
- Reclosers operate with 100% success probability.
- VOLL costs remain constant over the study period.

Based on above constraints and assumptions, GA is used for optimal placement of reclosers in feeder sections.

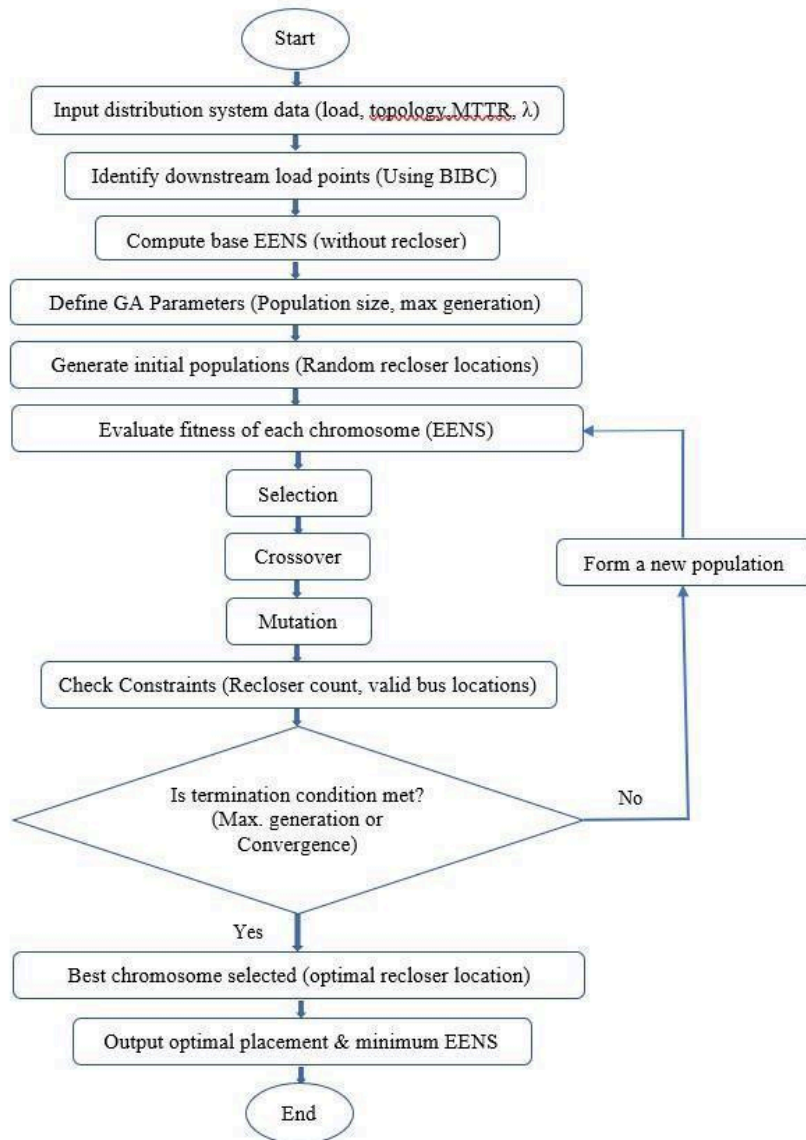


Figure 2: Flowchart of GA for selection of optimum number of recloser and location

To determine optimal recloser locations, a Genetic Algorithm was implemented in MATLAB. Candidate feeder branches were treated as decision variables, and each chromosome represents a possible recloser placement configuration. Reliability indices were recalculated for each candidate solution, and GA operators such as selection, crossover, and mutation were applied iteratively until convergence.

4. RESULTS AND DISCUSSION

Three years of tripping data for the feeders were obtained from the logbooks of the respective substations. Both momentary and sustained interruptions were considered.

Table 1: Basic Reliability parameter calculation of 11 kV Feeder-4 (Urban) Feeder

Year	Total Hours in a year (H)	FOI (No. of Failure (NF))	IT (Outage) hrs	Failure Rate ($\lambda_a=NF/H$)	MTTR (D=IT/NF)
2078/79	8760	158	16.32	0.02	0.10
2079/80	8760	206	15.05	0.02	0.07
2080/81	8760	216	17.72	0.02	0.08
Average		193.33	16.36	0.02	0.09

The average failure rate is 0.02 failures per hour, and the average MTTR is 0.09 hours, which is relatively low. This is attributed to the shorter length of the urban feeder and reduced exposure to vegetation.

Table 2: Basic Reliability parameter calculation of 11 kV Khoplang (Rural) feeder

Year	Total Hours in a year (H)	FOI (No. of Failure (NF))	IT (Outage) hrs	Failure Rate ($\lambda_a=NF/H$)	MTTR (D=IT/NF)
2078/79	8760	646	74.30	0.07	0.12
2079/80	8760	950	115.77	0.11	0.12
2080/81	8760	1006	93.55	0.11	0.09
Average		867.33	94.54	0.10	0.11

The average failure rate is 0.10 failures per hour, which is relatively high for a distribution feeder. The average MTTR is 0.11 hours, this indicates that most of the faults are temporary faults and restored relatively quickly.

The MATLAB using GA will select the optimum number of recloser and location, based on reduction in EENS value with variation of number of recloser.

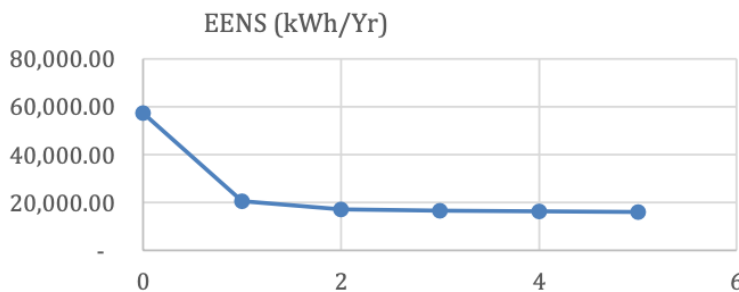


Figure 3: Variation of EENS with no. of recloser (urban feeder)

In case of urban feeder the optimum number of recloser is 2 and their locations are at branch 16 and 40; the ETAP model with optimum number of recloser is shown below;

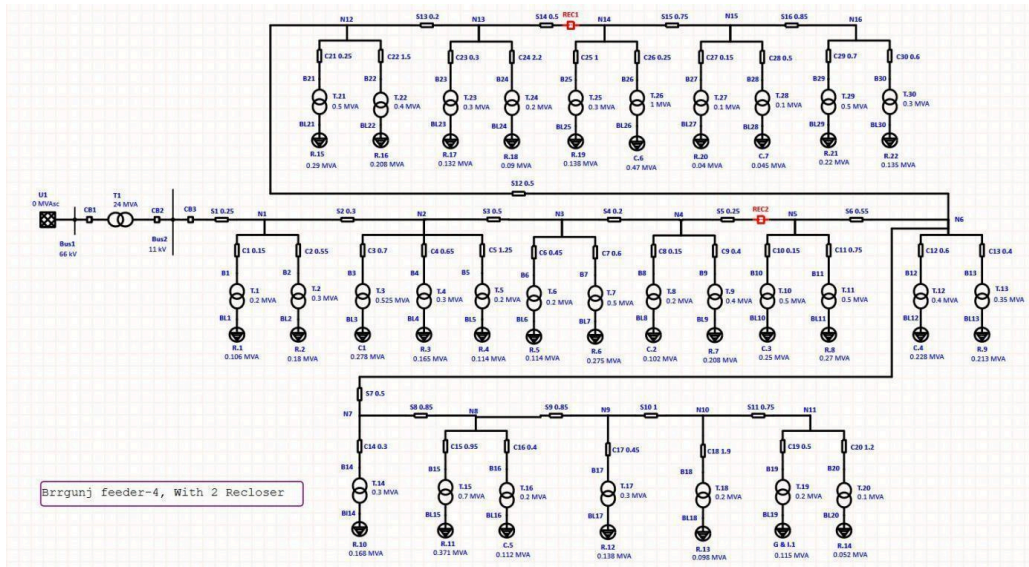


Figure 4: ETAP model of Feeder-4 (Urban feeder) with optimum number of recloser

Table 3: Reliability indices of feeder-4 (Base case and with optimum recloser)

Reliability Indices	Unit	Base Case	With 2 Recloser	% Improved
SAIDI	hr./Cust. Yr	12.6748	5.1618	59.28
SAIFI	Int./Cust. Yr	2.5977	1.6656	35.88
CAIDI	hr./Cust. Intr.	4.879	3.099	36.48
EENS	kWh/yr	57357	22981	59.93

Similarly for rural feeder the optimum number of recloser is 4 and their locations are at branch at 29,39,47 and 77.

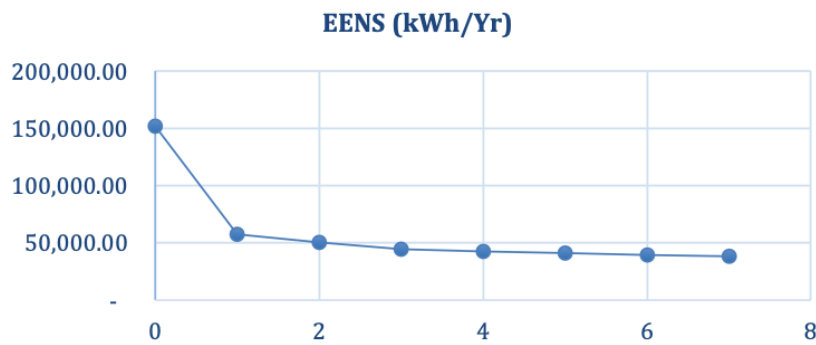


Figure 5: Variation of EENS with no. of recloser (rural feeder)

The ETAP model with optimum number of recloser is shown below;

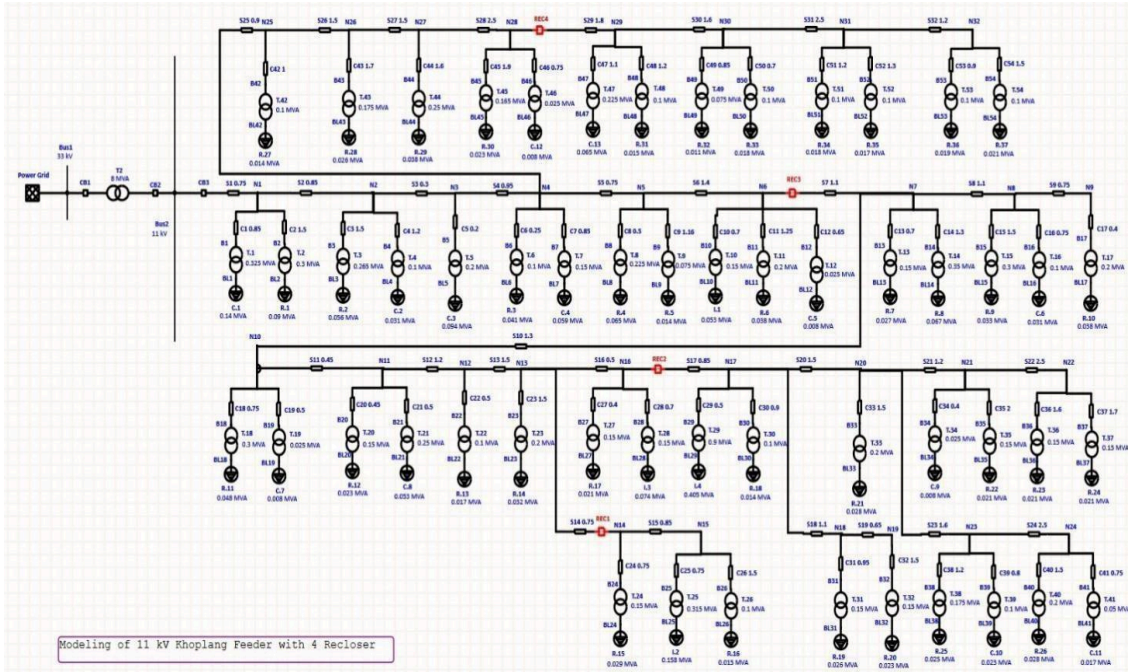


Figure 6: ETAP model of Khoplang (Rural) feeder with optimum number of recloser

Table 4: Reliability indices of Khoplang (Rural) Feeder (base case and using optimum recloser)

Reliability Indices	Unit	Base Case	With 4 Recloser	% Improved
SAIDI	hr./Cust. Yr	77.06	33.4307	56.62
SAIFI	Int./Cust. Yr	12.7309	6.7504	46.98
CAIDI	hr./Cust. Intr.	6.053	4.952	18.19
EENS	kWh/yr	151696	70433	53.57

Base-case results showed significantly poorer reliability performance in the rural feeder. Optimal installation of two reclosers in the urban feeder and four in the rural feeder reduced SAIDI and EENS by more than 50%.

Table 5: Cost Benefit Analysis of Feeder-4 (Urban) and Khoplang (Rural) Feeder

Descriptions	Unit	Urban (Feeder-4) Feeder	Rural (Khoplang) Feeder	Remarks
Base Case EENS	kWh/yr	57,357.00	151,696.00	

EENS with optimal recloser	kWh/yr	22,981.00	70,433.00	
Annual Energy Saving	kWh/yr	34,376.00	81,263.00	
Avg. per unit Cost	Rs.	9.63	8.23	
Annual Benefit	Rs.	331,040.88	668,794.49	
BCR		2.09	2.02	
Payback period	Years	3.72	3.68	

For the urban feeder (Feeder-4), the base-case EENS is 57,357 kWh/year, which is reduced to 22,981 kWh/year after installing optimally placed reclosers. This results in an annual energy saving of 34,376 kWh/year. Considering an average per-unit energy cost of Rs. 9.63 per kWh, the annual economic benefit obtained from reduced energy not supplied is Rs. 331,040.88.

Similarly, for the rural feeder (Khoplang), the base-case EENS of 151,696 kWh/year is reduced to 70,433 kWh/year after optimal recloser placement, yielding an annual energy saving of 81,263 kWh/year. With an average per-unit energy cost of Rs. 8.23 per kWh, the corresponding annual benefit is Rs. 668,794.49. The higher energy saving in the rural feeder is attributed to its longer feeder length and higher base-case outage exposure. Economic evaluation confirmed benefit–cost ratios exceeding 2.0 and payback periods below four years.

5. CONCLUSIONS

This study presented an optimization-based approach for determining the optimal placement of auto-reclosers in rural and urban 11 kV distribution feeders of Nepal. Analytical reliability modeling and ETAP simulation were used to evaluate base-case performance, while a Genetic Algorithm was employed to identify optimal recloser locations considering both reliability improvement and economic benefit.

The results demonstrated that optimal installation of two reclosers in the urban feeder and four in the rural feeder significantly reduced SAIDI and EENS by more than 50% in both cases. Cost–benefit analysis confirmed the economic feasibility of the proposed solution, with benefit–cost ratios exceeding 2.0 and payback periods of less than four years.

Overall, the study confirms that systematic and optimization-based recloser placement is an effective and economically justified strategy for enhancing the reliability of Nepalese distribution systems.

6. SUGGESTIONS AND RECOMMENDATIONS

Based on the findings of this study, distribution utilities in Nepal are recommended to adopt optimization-based planning approaches for protective device placement rather than relying on heuristic practices. Rural feeders, due to their long radial structure and high fault exposure, require greater sectionalization using auto-reclosers to improve reliability. Urban feeders, although relatively compact, can achieve higher economic efficiency through strategic recloser installation.

Utilities should maintain accurate outage records and reliability data to enhance modeling accuracy and support data-driven decision-making. Furthermore, reliability improvement projects should always incorporate cost–benefit analysis to ensure optimal allocation of investment resources.

Future research may consider integration of distributed generation, time-varying load models, communication-assisted reclosers, and smart grid technologies for further enhancement of distribution system reliability.

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