

Heuristic Evaluation of Recloser and Fuse Placement for Non-Supplied Energy Level Reduction in Radial Rural Distribution Grids

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Abstract This paper presents a heuristic evaluation framework for assessing the impact of recloser and fuse placement on the Non-Supplied Energy Level (NSEL) in radial rural distribution grids subjected to permanent faults. A mathematical formulation based on the operational state matrix is developed to calculate the NSEL for different protection device configurations, eliminating the need for iterative power flow algorithms and significantly reducing computational time. The proposed methodology employs heuristic criteria derived from standard utility practices to identify candidate locations for reclosers and fuses, reflecting real-world decision-making processes. Technical constraints including protection coordination, maximum devices in series, and exclusive installation are incorporated to ensure feasible configurations. The framework is validated on a 15-bus test system representative of Colombian rural distribution networks, where exhaustive enumeration of 504 feasible configurations reveals that strategic device placement can achieve NSEL reductions of up to 62.38% compared to the base case. The results demonstrate that fuse placement plays a more dominant role than recloser placement in NSEL reduction, and that the heuristic methodology achieves near-optimal performance within 1.22% of the best solution found through exhaustive enumeration. A comparative analysis against a greedy placement baseline and a random placement baseline is provided to contextualize the solution quality of the proposed heuristic. Additionally, a simplified economic assessment based on typical device cost ratios is discussed to illustrate the practical implications of the recommended configurations. The computational efficiency of the proposed approach enables rapid evaluation of multiple configurations, making it a practical tool for distribution system operators with limited investment budgets.

Keywords Reclosers; fuses; non-supplied energy level; radial distribution systems; rural grids; permanent faults; reliability; protection coordination; heuristic evaluation; operational state matrix

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Nomenclature

AGCB	Chu & Beasley Genetic Algorithm
DSO	Distribution System Operator
GA	Genetic Algorithm

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MILP	Mixed-Integer Linear Programming
MINLP	Mixed-Integer Nonlinear Programming
NSEL	Non-Supplied Energy Level
PSO	Particle Swarm Optimization

Binary Variables

$\mathbf{d}$	Complete decision vector of all binary variables
$\mathbf{x}$	Vector of recloser decision variables
$\mathbf{x}_0$	Base case recloser configuration vector
$\mathbf{y}$	Vector of fuse decision variables
$\mathbf{y}_0$	Base case fuse configuration vector
x_{ij}	Binary variable; 1 if a recloser is installed on branch ij , 0 otherwise
y_{ij}	Binary variable; 1 if a fuse is installed on branch ij , 0 otherwise

Parameters

λ_{ij}	Permanent fault rate of branch ij (faults/km/year)
kW_j	Active power demand at receiving node j of branch ij (kW)
$L_{\min}^F$	Minimum branch length threshold for fuse candidate selection (km)
$L_{\min}^R$	Minimum branch length threshold for recloser candidate selection (km)
l_{ij}	Length of branch ij (km)
m_F	Number of fuses to be installed (fixed)
m_R	Number of reclosers to be installed (fixed)
N_m^F	Maximum total number of fuses allowed
N_m^R	Maximum total number of reclosers allowed
N_{configs}	Total number of possible configurations
N_{FS}	Maximum number of fuses in series allowed
N_{RS}	Maximum number of reclosers in series allowed
$P_{\min}^R$	Minimum power flow threshold for recloser candidate selection (kW)
P_{ij}	Active power flowing through branch ij (kW)
r_{ij}	Average repair time for branch ij (hours)
T_C	Communication time for fault notification (hours)
T_L	Fault localization time (hours)
T_P	Preparation time to organize work crew (hours)

T_R Fault repair time (hours)

U_{ij} Annual unavailability of branch ij (hours/year)

Sets

$\mathcal{C}_F$ Set of candidate branches for fuse placement

$\mathcal{C}_R$ Set of candidate branches for recloser placement

Ω_{ij} Set of all network branches, indexed by (i, j)

Ω_{kl}^{ij} Set of branches kl located downstream of branch ij

Ω_{MF} Set of first branches of each main feeder (substation output)

Ω_{NCRF} Set of branch pairs where coordination between a recloser and a fuse is not feasible

Ω_{NCRR} Set of branch pairs where coordination between two reclosers is not feasible

Ω_{RP} Set of branches belonging to the main feeder trunk

Ω_{RS} Set of branches along a specific path from substation to terminal node

Variables

ΔNSEL Reduction in NSEL achieved by a given configuration

η Percentage reduction in NSEL

η_c Percentage reduction in NSEL for configuration c

$\lambda_{ij}^{(kl)}$ Failure rate of branch ij when fault occurs in branch kl

$\mathbf{M}$ Operational state matrix, dimension $n \times n$

NSEL Non-Supplied Energy Level (kWh/year)

$\text{NSEL}_{\text{base}}$ Base case NSEL with only substation protection

$M_{ij,kl}$ Operational state of branch ij when a fault occurs in branch kl

$r_{ij}^{(kl)}$ Repair time of branch ij when fault occurs in branch kl

$U_{ij}^{\text{contribution}}$ Unavailability contribution of branch ij to the total NSEL

U_{ij}^{total} Total unavailability of branch ij considering all possible faults

1. Introduction

The global energy landscape is undergoing an unprecedented transformation driven by the urgent need to decarbonize electricity generation, enhance energy security, and mitigate the adverse effects of climate change [1, 2]. Electric power distribution systems constitute a fundamental component of the overall electricity supply chain, as they are directly responsible for delivering energy to end-users and ensuring adequate levels of quality, security, and continuity of service [3, 4]. In developing countries, particularly in rural and remote areas, distribution networks face significant challenges in maintaining reliable service due to extended feeder lengths, low load density, limited investment capacity, and exposure to harsh environmental conditions [5, 6]. These factors collectively contribute to higher fault rates and prolonged outage durations, which disproportionately affect rural communities and hinder socioeconomic development [7, 8, 9].

Among the various indicators used to quantify service quality, the Non-Supplied Energy Level (NSEL) has emerged as a comprehensive metric that captures both the frequency and duration of supply interruptions [10, 11]. The NSEL represents the total amount of energy not delivered to consumers due to faults and outages, and it serves as a critical reference for regulatory penalties imposed on distribution system operators (DSOs) [12, 13]. Reducing the NSEL is therefore a primary objective for DSOs, as it directly impacts customer satisfaction, regulatory compliance, and financial performance [14]. In rural distribution grids, where permanent faults are the predominant cause of prolonged interruptions, the strategic placement of protection devices offers a cost-effective means of improving reliability and reducing the NSEL [15].

Reclosers and fuses are among the most widely used protection devices in distribution networks. Reclosers are automatic switching devices that can interrupt fault currents and automatically restore service after temporary faults, while fuses provide simple and cost-effective protection for lateral feeders and branches [16]. The strategic placement of these devices can significantly reduce the NSEL by isolating faults more rapidly, minimizing the number of affected customers, and enabling faster restoration of service [17, 18]. However, determining the optimal location of these devices is a complex combinatorial problem, particularly in radial rural networks with long feeders and multiple lateral branches [19]. The placement of reclosers and fuses must consider technical constraints such as protection coordination, maximum devices in series, and coordination with existing protection schemes, making the problem challenging to solve in practice [20].

The existing literature on protection device placement in distribution systems can be broadly categorized into three main approaches: mathematical programming, metaheuristic optimization, and heuristic methods. Mathematical programming approaches, including mixed-integer linear and nonlinear programming, provide exact solutions but often struggle with the combinatorial complexity of large-scale networks [21, 22]. Metaheuristic optimization techniques, such as genetic algorithms [18], particle swarm optimization [22], and the Chu & Beasley Genetic Algorithm [23], have been widely applied to this problem due to their ability to explore large solution spaces efficiently. These methods have demonstrated success in identifying high-quality configurations for various test systems. However, metaheuristic approaches typically require extensive parameter tuning and may not guarantee global optimality, which limits their practical applicability for DSOs with limited computational resources and expertise. Heuristic methods based on engineering judgment and utility practices offer a more practical alternative, providing reasonable solutions that align with real-world operational constraints and decision-making processes [5].

Despite the extensive research on protection device placement, several gaps remain in the literature. First, most existing studies focus on optimizing a combination of reliability and investment costs, often neglecting the detailed analysis of how individual device configurations influence the NSEL. Second, the majority of proposed methods rely on optimization algorithms that may not be easily accessible to DSOs in developing countries, where computational resources and technical expertise may be limited. Third, few studies provide a comprehensive evaluation of the solution space for a fixed number of devices, which is often the practical constraint faced by DSOs with budget limitations. Fourth, the role of fuses relative to reclosers in NSEL reduction is not always clearly quantified, despite fuses being significantly more cost-effective and widely used in rural networks. Fifth, and importantly for the present work, the operational state matrix approach—while conceptually related to established reliability evaluation techniques such as the analytical method based on failure modes and effect analysis—has not

been systematically adapted and validated for the specific problem of recloser and fuse placement in rural radial distribution grids with the level of detail presented here.

To address these gaps, this paper presents a comprehensive evaluation framework for assessing the impact of recloser and fuse placement on the NSEL in radial rural distribution grids subjected to permanent faults. The proposed approach makes the following specific contributions:

1. A mathematical formulation based on the operational state matrix is developed to calculate the NSEL for different protection device configurations, eliminating the need for iterative power flow algorithms and significantly reducing computational time. While the operational state matrix concept draws on established reliability evaluation principles, its systematic application to recloser and fuse placement evaluation in rural radial distribution grids—including the explicit modeling of restorable and non-restorable operational states—represents a novel adaptation for this specific problem domain.
2. A heuristic methodology grounded in standard utility practices is employed to identify candidate locations for reclosers and fuses, reflecting the real-world decision-making processes of DSOs and providing practical recommendations that can be readily implemented. The heuristic criteria are explicitly defined with numerical thresholds to ensure reproducibility.
3. The NSEL calculation model is separated from the solution methodology, enabling a clear understanding of how device configurations influence system reliability and facilitating the analysis of individual device contributions. This separation also allows the NSEL calculation to be independently validated against established analytical reliability methods.
4. A comprehensive evaluation of the solution space for a fixed number of devices is performed, quantifying the variability of NSEL reduction achievable and demonstrating the importance of strategic device placement. The exhaustive enumeration within the heuristic candidate set provides a benchmark against which the performance of the heuristic selection can be assessed.
5. The methodology is validated on a 15-bus test system representative of Colombian rural distribution networks, with exhaustive enumeration of 504 feasible configurations, providing insights into the relative importance of recloser versus fuse placement. A comparative analysis against greedy and random placement baselines is also provided to contextualize the solution quality of the proposed heuristic.
6. A simplified economic assessment based on typical device cost ratios is included to illustrate the practical cost-benefit implications of the recommended configurations, addressing the need for economic considerations in device placement decisions.

The scope of this work is limited to the evaluation of recloser and fuse placement in radial rural distribution systems under permanent faults. Automatic transfer switches are not considered in this analysis, as their evaluation is reserved for future work. The proposed methodology does not guarantee global optimality, as it relies on heuristic criteria for candidate selection; however, it provides near-optimal configurations within 1.22% of the best solution found through exhaustive enumeration within the candidate set for the test system considered. It is important to note that the exhaustive enumeration is performed within the heuristic candidate set; therefore, the near-optimality claim is relative to that restricted solution space, not to the full combinatorial space of all possible device locations. The methodology is designed for application by DSOs with limited computational resources, offering a practical and transparent framework for improving distribution system reliability.

The remainder of this paper is organized as follows. Section 2 presents the mathematical formulation of the problem, including the NSEL estimation, operational state matrix, decision variables, objective function, operational constraints, and performance metrics. Section 3 describes the heuristic methodology for device placement evaluation, including the network characterization, base case evaluation, candidate location identification, configuration enumeration, and results analysis. Section 4 presents the rural test feeder data used for validation. Section 5 presents the numerical validations, including the solution space evaluation and results analysis. Finally, Section 6 presents the conclusions and outlines directions for future work.

2. Mathematical Formulation of the Problem

The operational improvement of electric power distribution systems through the strategic placement of reclosers and fuses represents a critical challenge for DSOs, particularly in radial rural networks where reliability indices are significantly affected by permanent faults [23]. The NSEL serves as a comprehensive indicator that quantifies the impact of protection device allocation on service continuity [12]. This section presents the mathematical formulation developed to evaluate the effect of reclosers and fuses on the NSEL in radial distribution systems.

2.1. Non-Supplied Energy Estimation

The classical approach for calculating the non-supplied energy level in a distribution system is given by (1):

$$\text{NSEL} = \sum_{(i,j) \in \Omega_{ij}} \lambda_{ij} r_{ij} P_{ij} l_{ij} \quad (1)$$

where λ_{ij} represents the permanent fault rate of branch ij (faults/km/year), r_{ij} is the average repair time (hours), l_{ij} is the branch length (km), and P_{ij} is the active power flowing through the branch (kW). It is important to note that the failure rate λ_{ij} in this work is expressed in faults per kilometer per year, and the branch length l_{ij} is explicitly included in the classical formulation.

To simplify the computational burden and avoid the need for iterative load flow algorithms, a reduced analysis based on annual unavailability U_{ij} is proposed. The unavailability is defined as the product of the failure rate and repair time [24]:

$$U_{ij} = \lambda_{ij} r_{ij} \quad (2)$$

Consequently, the non-supplied energy can be approximated as the sum of the unavailability of each branch multiplied by the demand at its receiving node kW_j , as shown in (3):

$$\text{NSEL} = \sum_{(i,j) \in \Omega_{ij}} U_{ij} kW_j \quad (3)$$

This reduced formulation eliminates the need for power flow calculations, significantly reducing computational time while maintaining acceptable accuracy for reliability assessment studies [24]. It is important to clarify that in the reduced formulation, the failure rate λ_{ij} is treated as an aggregate failure rate for the entire branch (i.e., the product of the per-kilometer failure rate and the branch length), such that $U_{ij} = \lambda_{ij} r_{ij}$ represents the annual unavailability of the branch as a whole. This ensures dimensional consistency between (1) and (3). The reduced formulation assumes that the active power demand at the receiving node kW_j is a reasonable proxy for the power flowing through the branch for the purpose of unavailability contribution, which is a common approximation in radial distribution reliability studies where downstream load aggregation is dominated by the receiving node demand.

2.2. Operational States of Network Branches

To determine the correct values of λ_{ij} and r_{ij} for each scenario, the branch states must be identified based on the installed protection devices. Each branch ij can exhibit three possible operational states, depending on the location of permanent faults and the configuration of reclosers and fuses [24]:

- **Normal (N):** The branch operates without alteration when a fault occurs elsewhere.
- **Restorable (R):** The branch returns to normal operation fed by the original substation after fault isolation and repair.
- **Non-restorable (I):** The branch cannot be energized from the substation (i.e., it is the fault location itself or is isolated downstream).

The failure rate and repair time assigned to each branch depend on its operational state. This relationship is summarized in Table 1, where the times T_C , T_P , T_L , and T_R represent the communication, preparation, localization,

and repair times, respectively [25]. It is important to clarify that the failure rate λ in Table 1 refers to the failure rate of the faulted branch kl (i.e., λ_{kl}), while the repair time is assigned to the affected branch ij according to its operational state. Specifically, when a fault occurs in branch kl , the failure rate used in the unavailability calculation for any affected branch ij is λ_{kl} , and the repair time $r_{ij}^{(kl)}$ is determined by the operational state of branch ij as per Table 1. This distinction is crucial for correctly computing the total unavailability in (4).

Table 1. Assignment of failure rates and repair times based on operational state for recloser and fuse placement evaluation.

State	Failure Rate	Repair Time
N	0	0
R	λ_{kl}	$T_C + T_P + T_L$
I	λ_{kl}	$T_C + T_P + T_L + T_R$

2.3. Operational State Matrix and NSEL Calculation

The evaluation of the NSEL for each candidate configuration requires determining the operational state of every branch. This is achieved by constructing the *Operational State Matrix* $\mathbf{M} \in \{N, R, I\}^{n \times n}$, where n is the number of branches. Each element $M_{ij,kl}$ represents the state of branch ij when a permanent fault occurs in branch kl [25].

The matrix is built using a tree-search strategy that identifies operational areas. An operational area is defined as a region of the circuit delimited by the location of protection devices and/or terminal nodes. Two types of areas are considered:

- **Type 1:** Areas whose head protection is a recloser or main protection.
- **Type 2:** Areas whose head protection is a fuse.

The operational state matrix is constructed through the following procedure:

1. Identify all operational areas based on the location of reclosers (x_{ij}) and fuses (y_{ij}).
2. For each branch kl , simulate a permanent fault and determine the state of every other branch ij according to:
 - If branch ij is upstream of the protection device that isolates the fault, its state is **Normal (N)**.
 - If branch ij is downstream of the isolating device but can be re-energized from the substation after fault isolation, its state is **Restorable (R)**.
 - Otherwise, branch ij is **Non-restorable (I)**.
3. Populate matrix $\mathbf{M}$ with the determined states.

To illustrate the construction of the operational state matrix, consider a simple radial feeder with three branches in series: branch 1–2, branch 2–3, and branch 3–4, with a recloser installed on branch 1–2 (at the substation output) and a fuse installed on branch 3–4. For a permanent fault on branch 2–3, the recloser on branch 1–2 operates to isolate the fault. Branch 1–2 remains Normal (N) because it is upstream of the recloser. Branch 2–3 is Non-restorable (I) because it is the faulted branch and cannot be energized until repaired. Branch 3–4 is Restorable (R) because after the fuse on branch 3–4 is replaced or the fault is isolated, it can be re-energized from the substation through the recloser once branch 2–3 is repaired. This example illustrates how the operational state matrix captures the impact of protection device coordination on the reliability of each branch.

Once $\mathbf{M}$ is constructed, the failure rate $\lambda_{ij}^{(kl)}$ and repair time $r_{ij}^{(kl)}$ for each branch ij when a fault occurs in branch kl are assigned according to Table 1.

The total unavailability for branch ij considering all possible fault locations is:

$$U_{ij}^{\text{total}} = \sum_{(k,l) \in \Omega_{ij}} \lambda_{kl} r_{ij}^{(kl)} \quad (4)$$

Finally, the NSEL is calculated as:

$$\text{NSEL} = \sum_{(i,j) \in \Omega_{ij}} U_{ij}^{\text{total}} kW_j \quad (5)$$

It is important to note that the operational state matrix approach used in this work is conceptually related to established analytical reliability evaluation methods for distribution systems, particularly those based on failure modes and effect analysis (FMEA) and the method of sections. The novelty of the present application lies in the systematic integration of this matrix approach with the specific problem of recloser and fuse placement evaluation in rural radial distribution grids, including the explicit consideration of restorable and non-restorable states and the coordination constraints that govern device placement.

2.4. Decision Variables

The following binary decision variables are defined for the evaluation of recloser and fuse configurations:

- x_{ij} : Indicates whether a recloser is installed on branch ij ($x_{ij} = 1$) or not ($x_{ij} = 0$).
- y_{ij} : Indicates whether a fuse is installed on branch ij ($y_{ij} = 1$) or not ($y_{ij} = 0$).

The complete decision vector $\mathbf{d}$ is represented as:

$$\mathbf{d} = [x_{11}, x_{12}, \dots, x_{ij}, \dots, y_{11}, y_{12}, \dots, y_{ij}, \dots]^T \quad (6)$$

2.5. Objective Function

The objective of this research is to evaluate the effect of recloser and fuse configurations on the NSEL. Therefore, the objective function is defined as the minimization of the total non-supplied energy level for a given configuration of reclosers and fuses:

$$\min f(\mathbf{x}, \mathbf{y}) = \text{NSEL}(\mathbf{x}, \mathbf{y}) \quad (7)$$

Expanding the NSEL calculation using the operational state matrix approach, the objective function can be expressed as:

$$\min f(\mathbf{x}, \mathbf{y}) = \sum_{(i,j) \in \Omega_{ij}} \left[\sum_{(k,l) \in \Omega_{ij}} \lambda_{kl} r_{ij}^{(kl)}(\mathbf{x}, \mathbf{y}) \right] kW_j \quad (8)$$

2.6. Operational Constraints

The evaluation of recloser and fuse configurations is subject to a set of technical and operational constraints that guarantee the feasibility and security of the resulting configuration.

2.6.1. Mandatory Protection at Substation A protection device must exist at the output of each substation feeder. For the set of first branches of each main feeder Ω_{MF} :

$$x_{ij} = 1 \quad \forall (i, j) \in \Omega_{MF} \quad (9)$$

2.6.2. Exclusive Installation At most, one protection device can be installed on a given branch:

$$x_{ij} + y_{ij} \leq 1 \quad \forall (i, j) \in \Omega_{ij} \quad (10)$$

2.6.3. Device Limitations on Main Feeders Only reclosers can be installed on the main feeder trunks. For the set of branches belonging to the main feeder Ω_{RP} :

$$\sum_{(i,j) \in \Omega_{RP}} y_{ij} = 0 \quad (11)$$

2.6.4. Maximum Devices in Series The number of reclosers and fuses in series along any path from the substation to a terminal node is limited to N_{RS} and N_{FS} , respectively:

$$\sum_{(i,j) \in \Omega_{RS}} x_{ij} \leq N_{RS} \quad \forall \text{paths} \quad (12)$$

$$\sum_{(i,j) \in \Omega_{RS}} y_{ij} \leq N_{FS} \quad \forall \text{paths} \quad (13)$$

where Ω_{RS} represents the set of branches along a specific path from the substation to a terminal node.

2.6.5. Protection Coordination No recloser may be placed downstream of a fuse to ensure proper coordination:

$$x_{kl} + y_{ij} \leq 1 \quad \forall (i,j) \in \Omega_{kl}^{ij} \quad (14)$$

where Ω_{kl}^{ij} represents all branches kl located downstream of branch ij .

2.6.6. Coordination Incompatibilities When coordination between two reclosers or between a recloser and a fuse is not feasible:

$$x_{ij} + x_{kl} \leq 1 \quad \forall (i,j) \wedge \forall (k,l) \in \Omega_{NCRR} \quad (15)$$

$$x_{ij} + y_{kl} \leq 1 \quad \forall (i,j) \wedge \forall (k,l) \in \Omega_{NCRF} \quad (16)$$

where Ω_{NCRR} and Ω_{NCRF} represent the sets of branch pairs where coordination is not possible for two reclosers or a recloser-fuse pair, respectively. In this work, the coordination constraints are defined based on standard utility practice: no recloser is placed downstream of a fuse, and no two reclosers are placed in series without an intermediate fuse or sectionalizer. The specific coordination pairs are determined by the topological structure of the test feeder and the standard time-current coordination principles, which are assumed to be satisfied for all feasible configurations generated by the heuristic. It is acknowledged that a detailed protection coordination study including fault current levels, time-current curves, and reclosing sequences would be required for actual deployment; however, such detailed coordination is beyond the scope of the present evaluation framework, which focuses on the reliability impact of device placement.

2.6.7. Maximum Number of Devices Limits on the total number of devices to be installed:

$$\sum_{(i,j) \in \Omega_{ij}} x_{ij} \leq N_m^R \quad (17)$$

$$\sum_{(i,j) \in \Omega_{ij}} y_{ij} \leq N_m^F \quad (18)$$

where N_m^R and N_m^F are the maximum allowable numbers of reclosers and fuses, respectively.

2.7. Complete Model Summary

The complete evaluation model for analyzing the effect of reclosers and fuses on the NSEL is a binary mixed-integer nonlinear programming (MINLP) problem with an algorithmic representation, summarized as:

$$\text{Minimize: } \text{NSEL}(\mathbf{x}, \mathbf{y}) = \sum_{(i,j) \in \Omega_{ij}} U_{ij}^{\text{total}}(\mathbf{x}, \mathbf{y}) kW_j$$

Subject to:

$$\begin{aligned} x_{ij} &= 1 \quad \forall (i, j) \in \Omega_{MF} \\ x_{ij} + y_{ij} &\leq 1 \quad \forall (i, j) \in \Omega_{ij} \\ \sum_{(i,j) \in \Omega_{RP}} y_{ij} &= 0 \\ \sum_{(i,j) \in \Omega_{RS}} x_{ij} &\leq N_{RS}, \quad \sum_{(i,j) \in \Omega_{RS}} y_{ij} \leq N_{FS} \\ x_{kl} + y_{ij} &\leq 1 \quad \forall (i, j) \in \Omega_{kl}^{ij} \\ x_{ij} + x_{kl} &\leq 1 \quad \forall (i, j) \wedge \forall (k, l) \in \Omega_{NCRR} \\ x_{ij} + y_{kl} &\leq 1 \quad \forall (i, j) \wedge \forall (k, l) \in \Omega_{NCRF} \\ \sum_{(i,j) \in \Omega_{ij}} x_{ij} &\leq N_m^R, \quad \sum_{(i,j) \in \Omega_{ij}} y_{ij} \leq N_m^F \\ x_{ij}, y_{ij} &\in \{0, 1\} \end{aligned} \tag{19}$$

The non-linear nature of this problem arises from the dynamic calculation of the NSEL, which depends on the structure of the operational state matrix $\mathbf{M}$, generated by the specific binary configuration of the variables. It is worth noting that the operational constraints are linear in the binary decision variables, and the nonlinearity is confined to the objective function evaluation.

2.8. Performance Metrics

To evaluate the effect of recloser and fuse configurations, the following metrics are defined:

2.8.1. NSEL Reduction The reduction in NSEL achieved by a given configuration compared to the base case (only substation protection) is calculated as:

$$\Delta \text{NSEL} = \text{NSEL}_{\text{base}} - \text{NSEL}(\mathbf{x}, \mathbf{y}) \tag{20}$$

2.8.2. Percentage Reduction The percentage reduction in NSEL is defined as:

$$\eta = \frac{\text{NSEL}_{\text{base}} - \text{NSEL}(\mathbf{x}, \mathbf{y})}{\text{NSEL}_{\text{base}}} \times 100\% \tag{21}$$

2.8.3. Unavailability Contribution The contribution of each branch to the total system unavailability is:

$$U_{ij}^{\text{contribution}} = U_{ij}^{\text{total}} kW_j \tag{22}$$

These metrics allow for a comprehensive assessment of how different recloser and fuse configurations impact the overall system reliability and the NSEL in radial rural distribution grids.

3. Heuristic Methodology for Device Placement Evaluation

The evaluation of recloser and fuse configurations in this research is conducted using a heuristic approach based on standard utility practices, rather than metaheuristic optimization algorithms. This methodology reflects the real-world decision-making processes employed by distribution system operators, where practical considerations,

regulatory requirements, and engineering judgment guide the selection of device locations. The proposed heuristic approach provides a systematic framework for assessing the impact of different protection configurations on the NSEL.

3.1. Overview of the Heuristic Evaluation Framework

The proposed methodology is structured around four main stages, as illustrated in Figure ??:

1. **Network characterization:** Collection and organization of all relevant network data, including topology, load information, and reliability parameters.
2. **Base case evaluation:** Calculation of the NSEL for the system with only substation protection, establishing the reference value.
3. **Identification of candidate locations:** Selection of potential branches for recloser and fuse installation based on heuristic criteria derived from utility practices.
4. **Configuration evaluation and analysis:** Systematic assessment of different device configurations and comparison of results.

This structured approach ensures a comprehensive and repeatable evaluation of protection device configurations, enabling distribution system operators to make informed decisions regarding device placement.

3.2. Network Characterization

The first step of the methodology consists of characterizing the distribution network in terms of its physical and operational parameters. The required information includes:

- **Topological data:** Single-line diagram of the network, including all nodes and branches, with clear identification of the main feeder and lateral branches.
- **Load data:** Active and reactive power demand at each node, typically obtained from historical measurements or load forecasting studies.
- **Reliability parameters:** Permanent fault rates (λ_{ij}), repair times (T_R), communication times (T_C), preparation times (T_P), and localization times (T_L) for each branch.
- **Existing protection devices:** Identification of any protection devices already installed in the network, such as substation breakers or existing fuses.

For the 15-bus test system considered in this paper, the network characterization data are presented in Tables 2 and 3, with the topological configuration shown in Figure 1.

3.3. Base Case Evaluation

The base case configuration is defined as the system with only the mandatory protection device installed immediately downstream of the substation. This configuration serves as the reference for evaluating the impact of additional protection devices. It is acknowledged that in practice, utilities may already have some protection devices installed; however, for the purpose of this evaluation framework, the base case with only substation protection provides a clear and consistent reference point that isolates the incremental benefit of additional device placement.

The NSEL for the base case is calculated using the operational state matrix approach described in Section 2.3:

$$\text{NSEL}_{\text{base}} = \sum_{(i,j) \in \Omega_{ij}} U_{ij}^{\text{total}}(\mathbf{x}_0, \mathbf{y}_0) \cdot kW_j \quad (23)$$

where $\mathbf{x}_0$ and $\mathbf{y}_0$ represent the base case configuration with only substation protection ($x_{1,2} = 1$, all other $x_{ij} = 0$ and $y_{ij} = 0$).

For the 15-bus test system, the base case NSEL is 14,369.08 kWh/year, which provides the reference value $\text{NSEL}_{\text{base}}$ for evaluating the effectiveness of different device configurations.

3.4. Identification of Candidate Locations

Based on standard utility practices and engineering judgment, candidate locations for reclosers and fuses are identified. This step is critical, as the quality of the evaluation depends on the selection of appropriate candidate branches.

3.4.1. Criteria for Recloser Candidate Selection Reclosers are considered for installation on main feeder sections that satisfy one or more of the following criteria:

1. **Feeder segmentation:** Branches located at approximately 5–8 km intervals along the main feeder to divide long feeders into manageable segments.
2. **Branching points:** Branches immediately upstream of points where lateral feeders connect to the main trunk.
3. **Load concentration:** Branches located before major load concentrations or critical customers.
4. **Length threshold:** Branches with length $L_{ij} \geq L_{\min}^R$, where $L_{\min}^R$ is a threshold value defined by utility standards.

The set of candidate recloser branches $\mathcal{C}_R$ is formally defined as:

$$\mathcal{C}_R = \{(i, j) \in \Omega_{ij} : L_{ij} \geq L_{\min}^R \vee P_{ij} \geq P_{\min}^R \vee \text{branch } (i, j) \text{ is a branching point}\} \quad (24)$$

where L_{ij} is the branch length, P_{ij} is the power flow, and $L_{\min}^R$ and $P_{\min}^R$ are threshold values. For the 15-bus test system, the numerical thresholds used are $L_{\min}^R = 3.0$ km and $P_{\min}^R = 100$ kW. These values are selected based on typical utility practices for rural distribution networks, where reclosers are typically placed at intervals of 5–8 km or at major branching points. The same thresholds are used consistently throughout the study.

3.4.2. Criteria for Fuse Candidate Selection Fuses are considered for installation on lateral feeders and long branches that satisfy one or more of the following criteria:

1. **Lateral feeder heads:** Branches at the head of each lateral feeder to protect the main feeder from faults on branches.
2. **Long laterals:** Branches on laterals longer than 1–2 km, where additional fuses may be placed at intermediate points.
3. **Load density:** Branches in areas with higher customer density.

The set of candidate fuse branches $\mathcal{C}_F$ is formally defined as:

$$\mathcal{C}_F = \{(i, j) \in \Omega_{ij} : \text{branch } (i, j) \text{ is a lateral head or } L_{ij} \geq L_{\min}^F\} \quad (25)$$

where $L_{\min}^F$ is a threshold value defined by utility standards. For the 15-bus test system, the numerical threshold used is $L_{\min}^F = 1.5$ km, consistent with typical utility practice for fuse placement on lateral feeders.

For the 15-bus test system, this heuristic selection process yields $n_R = 4$ candidate recloser branches and $n_F = 9$ candidate fuse branches. It is important to clarify that the classification of branches as main feeder or lateral is determined by the topological structure of the test system: branches 1–2, 2–3, 3–4, and 4–5 form the main feeder trunk, while all other branches are laterals. The candidate recloser branches are 2–3, 3–4, 2–8, and 3–12, which are either branching points or segments of the main feeder with length exceeding the threshold. The candidate fuse branches are 4–5, 5–6, 5–7, 8–9, 9–10, 10–11, 12–13, 13–14, and 13–15, all of which are lateral heads or long laterals.

3.5. Configuration Enumeration and Evaluation

Once the candidate locations have been identified, the next step consists of enumerating all possible configurations that satisfy the operational constraints defined in Section 2.6. For a fixed number of reclosers (m_R) and fuses (m_F), the total number of possible configurations is:

$$N_{\text{configs}} = \binom{n_R}{m_R} \cdot \binom{n_F}{m_F} \quad (26)$$

where $n_R = |\mathcal{C}_R|$ and $n_F = |\mathcal{C}_F|$.

For each configuration, the NSEL is evaluated using the operational state matrix approach described in Section 2.3. The evaluation procedure is summarized in Algorithm 1.

Algorithm 1 NSEL Evaluation for a Given Recloser and Fuse Configuration

Input: Network data, configuration $(\mathbf{x}, \mathbf{y})$
Output: NSEL value
Initialize $\mathbf{M} \leftarrow \mathbf{0}$
Identify operational areas based on $\mathbf{x}, \mathbf{y}$
for each branch $kl \in \Omega_{ij}$ **do**
 Simulate permanent fault on branch kl
 for each branch $ij \in \Omega_{ij}$ **do**
 Determine state $M_{ij,kl}$ using operational area analysis
 Assign failure rate $\lambda_{ij}^{(kl)}$ and repair time $r_{ij}^{(kl)}$ based on $M_{ij,kl}$
 end for
end for
Calculate total unavailability for each branch: $U_{ij}^{\text{total}} = \sum_{(k,l)} \lambda_{kl} \cdot r_{ij}^{(kl)}$
Calculate NSEL: $\text{NSEL} = \sum_{(i,j)} U_{ij}^{\text{total}} \cdot kW_j$
return NSEL

The evaluation of all feasible configurations provides a comprehensive understanding of the solution space and enables the identification of configurations that achieve significant NSEL reductions while respecting operational constraints. It is important to emphasize that the exhaustive enumeration is performed within the heuristic candidate set, and therefore the near-optimality of the heuristic selection is relative to that restricted space, not to the full combinatorial space of all possible device locations.

3.6. Results Analysis and Recommendations

The evaluated configurations are analyzed based on the following performance metrics:

1. **NSEL reduction:** The absolute reduction in NSEL compared to the base case:

$$\Delta\text{NSEL} = \text{NSEL}_{\text{base}} - \text{NSEL}(\mathbf{x}, \mathbf{y}) \quad (27)$$

2. **Percentage reduction:** The relative reduction expressed as a percentage:

$$\eta = \frac{\text{NSEL}_{\text{base}} - \text{NSEL}(\mathbf{x}, \mathbf{y})}{\text{NSEL}_{\text{base}}} \times 100\% \quad (28)$$

3. **Unavailability contribution:** The contribution of each branch to the total system unavailability:

$$U_{ij}^{\text{contribution}} = U_{ij}^{\text{total}} \cdot kW_j \quad (29)$$

The analysis focuses on identifying configurations that achieve significant NSEL reductions with a relatively modest number of devices, making them attractive for practical implementation by distribution system operators. The results are presented in a systematic manner, highlighting key insights regarding the impact of recloser and fuse placement on the NSEL.

3.7. Discussion of the Heuristic Evaluation Framework

The proposed heuristic evaluation framework offers several advantages for practical application:

1. **Practical relevance:** The methodology is grounded in standard utility practices, ensuring that the recommendations are aligned with real-world engineering considerations.
2. **Computational efficiency:** The reduced formulation of the NSEL calculation eliminates the need for iterative power flow algorithms, enabling rapid evaluation of multiple configurations.
3. **Transparency:** The separation of the NSEL calculation model from the evaluation methodology provides clear insights into how device configurations influence system reliability.
4. **Flexibility:** The methodology can be applied to different distribution networks with appropriate adjustments to candidate selection criteria.

However, the methodology also has certain limitations:

- The approach does not guarantee global optimality, as it relies on heuristic rules for candidate selection rather than mathematical optimization. The near-optimality claim is relative to the restricted solution space defined by the heuristic candidate set.
- The candidate selection process may exclude some promising locations that do not satisfy the heuristic criteria.
- The methodology is designed for radial distribution systems and may not be directly applicable to meshed networks.
- The NSEL calculation uses approximate methods that may not capture all operational complexities, including the distinction between temporary and permanent faults, and the detailed protection coordination that would be required for actual deployment.
- The scalability of the exhaustive enumeration approach is limited by the combinatorial growth of the solution space. For larger networks, alternative solution strategies such as metaheuristic optimization or decomposition methods may be required.

Despite these limitations, the heuristic evaluation framework provides valuable insights into the effect of reclosers and fuses on the NSEL and offers practical recommendations that can be readily implemented by distribution system operators. The results presented in Section 5 demonstrate the effectiveness of the methodology in identifying near-optimal configurations with a relatively modest number of devices.

3.8. Remarks on Assumptions

The following remarks summarize the key assumptions adopted in the heuristic evaluation methodology:

Remark 1

The analysis assumes a purely radial network topology with no parallel paths, which is characteristic of typical rural distribution systems. All loads are modeled as constant power loads, and device failure rates are considered independent of environmental conditions. Protection coordination is assumed to be established according to standard time-current curves, ensuring selective fault isolation between reclosers and fuses. The specific coordination pairs are determined by the topological structure of the test feeder, and the coordination constraints are defined to prevent infeasible configurations such as a recloser downstream of a fuse.

Remark 2

The evaluation focuses exclusively on permanent faults, as these are the primary cause of prolonged supply interruptions and have the most significant impact on the NSEL. Transient faults, which are typically cleared by automatic reclosing, are not considered in the analysis. Furthermore, automatic transfer switches are not included in this study, as their analysis is reserved for future work; consequently, the transfer time associated with these devices is not considered. It is acknowledged that temporary faults are more frequent in rural distribution systems; however, their inclusion would require modeling of reclosing sequences and fuse-saving or fuse-blowing schemes, which is beyond the scope of the present evaluation framework and is identified as a direction for future work.

Remark 3

The failure rate λ_{ij} is expressed in faults per kilometer per year, and the branch length l_{ij} is explicitly included in the classical NSEL formulation. In the reduced formulation, the aggregate branch failure rate (product of per-kilometer failure rate and branch length) is used to maintain dimensional consistency. The repair time assigned to each affected branch depends on its operational state and the fault location, as described in Table 1.

4. Rural Test Feeder Data

To evaluate the influence of recloser and fuse allocation on the overall Non-Supplied Energy Level (NSEL) in radial distribution networks, a medium-voltage distribution system operated at 11.4 kV is employed as the test feeder. This voltage level is characteristic of typical rural distribution grids in Colombia. The nodal configuration and the interconnection of branches for this test system are depicted in Figure 1. The total active power demand of the network is 1122.5 kW, and the system operates at a nominal power factor of approximately 0.95 lagging.

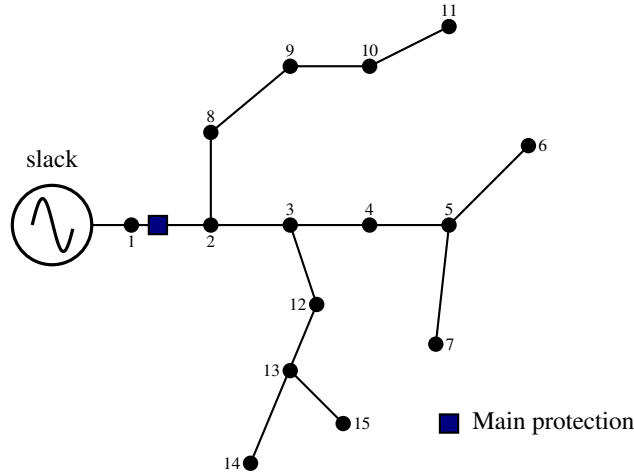


Figure 1. Single-line diagram of the 15-node medium voltage distribution network

The parametric information of the branches and load data, for the 15-node test feeder is listed in tables 2 and 3, respectively.

The failure rate λ_{ij} is expressed in faults per kilometer per year, and the branch length l_{ij} is provided in kilometers. The aggregate branch failure rate (product of λ_{ij} and l_{ij}) ranges from 0.0325 faults/year for branch 1–2 to 1.11 faults/year for branch 14–15, reflecting the longer lengths of lateral branches in rural distribution systems.

5. Numerical Validations

To evaluate the influence of recloser and fuse placement on the expected NSEL of the 15-bus test system, a base case is initially defined considering only the main protection device installed immediately downstream of the substation. In this configuration, the annual NSEL is 14,369.08 kWh/year, which constitutes the reference value $NSEL_{base}$.

Following the heuristic criteria based on standard utility practices described in Section 3, candidate locations for protection devices are selected. Four branches are identified as candidates for recloser installation: 2–3, 3–4,

Table 2. Node demand data for the 15-node test feeder.

Node	Active Power [kW]	Reactive Power [kvar]
1	0.0	0.0
2	75.0	24.65
3	67.5	22.19
4	37.5	12.33
5	50.0	16.43
6	112.5	36.98
7	150.0	49.30
8	45.0	14.79
9	75.0	24.65
10	75.0	24.65
11	45.0	14.79
12	150.0	49.30
13	50.0	16.43
14	25.0	8.22
15	15.0	4.93

Table 3. Line data for the 15-node test feeder including failure rates and repair times.

Branch		Main Prot.	λ_{ij}	l_{ij}	Time Parameters [h]			
Sending	Receiving	Indicator	[faults/km/yr]	[km]	T_R	T_C	T_P	T_L
1	2	1	0.05	0.65	1.00	0.50	0.50	0.50
2	3	0	0.05	3.50	1.00	0.50	0.50	0.50
3	4	0	0.05	3.70	1.00	0.50	0.50	0.50
4	5	0	0.10	1.85	1.00	0.50	0.50	0.50
5	6	0	0.10	2.30	2.00	0.50	0.50	0.75
5	7	0	0.10	1.75	2.00	0.50	0.50	0.75
2	8	0	0.12	2.50	1.00	0.50	0.50	0.50
8	9	0	0.12	1.15	2.00	0.50	0.50	0.75
9	10	0	0.12	0.75	2.00	0.50	0.50	1.00
10	11	0	0.12	4.50	2.00	0.50	0.50	1.00
3	12	0	0.15	6.25	1.00	0.50	0.50	0.50
12	13	0	0.15	3.30	1.00	0.50	0.50	0.50
13	14	0	0.15	5.20	2.00	0.50	0.50	1.00
14	15	0	0.15	7.40	2.00	0.50	0.50	1.00

2–8, and 3–12. Similarly, nine branches are identified as candidates for fuse installation: 4–5, 5–6, 5–7, 8–9, 9–10, 10–11, 12–13, 13–14, and 13–15. From these candidate locations, five representative configurations are analyzed to quantify their impact on the NSEL reduction. These five configurations were selected from the exhaustive enumeration to illustrate the key trade-offs and insights regarding recloser and fuse placement, specifically: (i) configurations that share the same fuse allocation but differ in recloser placement (Options 1–3) to isolate the effect of recloser location, and (ii) configurations that share the same recloser placement but differ in fuse allocation (Options 4–5) to isolate the effect of fuse location. This selection strategy ensures that the comparative analysis is systematic and informative.

5.1. Configuration Enumeration and Solution Space Dimension

Once the candidate locations for reclosers and fuses have been identified, the next step consists of enumerating all possible configurations that satisfy the constraints defined in Section 2.6. Let $n_R = |\mathcal{C}_R|$ be the number of candidate branches for recloser placement, and $n_F = |\mathcal{C}_F|$ be the number of candidate branches for fuse placement. If the number of reclosers to be installed is fixed to m_R and the number of fuses to m_F , the total number of possible configurations is given by:

$$N_{\text{configs}} = \binom{n_R}{m_R} \cdot \binom{n_F}{m_F} \quad (30)$$

This expression follows from the fact that the selection of recloser locations and fuse locations are independent combinatorial choices, subject to the coordination constraints that may eliminate some combinations. The product of two combinations accurately represents the dimension of the solution space for a fixed number of devices.

For the 15-bus test system considered in this paper, the candidate sets consist of $n_R = 4$ branches for recloser placement and $n_F = 9$ branches for fuse placement. For a fixed configuration with $m_R = 3$ reclosers and $m_F = 5$ fuses, the total number of possible combinations is:

$$N_{\text{configs}} = \binom{4}{3} \cdot \binom{9}{5} = 4 \cdot 126 = 504 \quad (31)$$

This relatively small solution space enables exhaustive enumeration of all feasible configurations, ensuring that the best-performing combination can be identified without the need for metaheuristic optimization algorithms. It is important to emphasize that this exhaustive enumeration is performed within the restricted candidate set, and therefore the best configuration identified is optimal within that set, not necessarily globally optimal over all possible device locations. The five configurations presented in Table 4 were selected from this exhaustive enumeration as described above.

5.2. Results and Discussion

Table 4 presents the numerical results for the five evaluated configurations, including the resulting NSEL and the percentage reduction achieved with respect to the base case.

Table 4. Numerical results for five configurations of recloser and fuse placement in the 15-bus test system.

Option	Reclosers	Fuses	NSEL _c [kWh/year]	η_c [%]
Base case	—	—	14,369.08	0.00
1	{2–3, 3–4, 3–12}	{4–5, 5–7, 9–10, 12–13, 13–15}	6,745.30	53.06
2	{2–3, 2–8, 3–12}	{4–5, 5–7, 9–10, 12–13, 13–15}	6,240.31	56.57
3	{2–3, 3–4, 2–8}	{4–5, 5–7, 9–10, 12–13, 13–15}	6,123.08	57.39
4	{3–4, 2–8, 3–12}	{5–6, 5–7, 8–9, 9–10, 12–13}	6,014.11	58.15
5	{3–4, 2–8, 3–12}	{4–5, 5–7, 8–9, 9–10, 12–13}	5,471.94	61.92

All five evaluated configurations achieve substantial NSEL reductions, ranging from 53.06% to 61.92% compared to the base case. This demonstrates that the strategic placement of reclosers and fuses, following the heuristic criteria based on standard utility practices, can significantly improve the reliability performance of radial rural distribution systems. Option 5 yields the best performance among all evaluated configurations, achieving an NSEL reduction of 61.92%, which corresponds to an absolute reduction of 8,897.14 kWh/year compared to the base case. This configuration incorporates reclosers on branches 3–4, 2–8, and 3–12, combined with fuses on branches 4–5, 5–7, 8–9, 9–10, and 12–13. Figure 2 illustrates the most effective location of the devices obtained in Option 5.

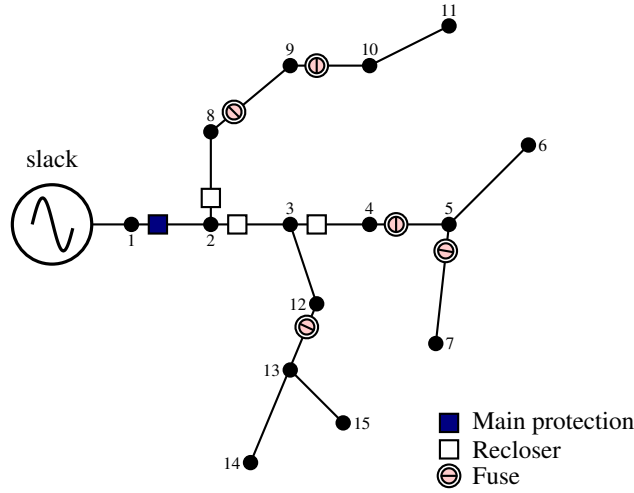


Figure 2. Best-performing configuration (Option 5) with recloser and fuse locations highlighted.

The results provide valuable insights into the influence of recloser placement. Configurations 1–3 share the same fuse allocation (branches 4–5, 5–7, 9–10, 12–13, and 13–15) but differ in recloser placement. Option 1 (reclosers on 2–3, 3–4, and 3–12) achieves a 53.06% reduction, while Option 2 (reclosers on 2–3, 2–8, and 3–12) reaches 56.57%, and Option 3 (reclosers on 2–3, 3–4, and 2–8) attains 57.39%. The progressive improvement from Options 1 to 3 confirms that protecting lateral feeders (branch 2–8) and strategically positioning reclosers at branching points significantly enhances NSEL reduction. The best recloser configuration (Option 3) outperforms the worst (Option 1) by 4.33 percentage points, demonstrating that recloser placement, while important, has a secondary effect compared to fuse allocation.

The comparison between Options 4 and 5 is particularly instructive, as both configurations share the same recloser placement (branches 3–4, 2–8, and 3–12) but differ in fuse allocation. Option 4 includes fuses on branches 5–6, 5–7, 8–9, 9–10, and 12–13, achieving a reduction of 58.15%. Option 5, which replaces fuse 5–6 with fuse 4–5, achieves a significantly higher reduction of 61.92%, an improvement of 3.77 percentage points. This difference underscores the critical role of protecting the lateral feeder branch 4–5 and highlights that strategic fuse placement—particularly on branches closer to the substation—can yield substantial additional NSEL reductions. The superior performance of Option 5 validates the heuristic recommendation that fuses should be prioritized at lateral feeder heads near the main trunk.

Overall, the results confirm that the heuristic methodology based on standard utility practices provides a robust and practical framework for improving distribution system reliability. The best-performing configuration (Option 5) achieves nearly 62% NSEL reduction using only three reclosers and five fuses, representing a significant improvement with a relatively modest number of devices. This makes it an attractive solution for distribution system operators with limited investment budgets, particularly in rural areas. All simulations were completed in less than 10 seconds, confirming the computational efficiency of the proposed evaluation framework, which eliminates the need for iterative power flow algorithms and facilitates rapid decision-making in distribution system planning.

The computational validation of the proposed methodology was conducted using a desktop computer equipped with an AMD Ryzen 7 3700 processor (2.3 GHz), 16 GB of RAM, and a 64-bit version of Windows 10. All simulations were implemented in MATLAB version 2025a using scripts developed by the authors.

5.3. Full Solution Space Evaluation

To provide a comprehensive understanding of the solution space and the variability of NSEL reduction achievable with a fixed number of devices, all 504 feasible configurations for the 15-bus test system—considering the installation of exactly 3 reclosers and 5 fuses—were exhaustively evaluated. This full enumeration allows the identification of the best and worst possible configurations within the heuristic candidate set, as well as the

characterization of the solution space distribution. The results of this exhaustive evaluation are summarized in Table 5.

Table 5. Summary statistics of NSEL for all feasible configurations with 3 reclosers and 5 fuses in the 15-bus test system.

Statistic	NSEL [kWh/year]	Reduction [%]	Compared to Best
Minimum (Best)	5,405.41	62.38	—
Mean	6,904.46	51.95	+1,499.05 kWh/year
Maximum (Worst)	9,301.13	35.27	+3,895.72 kWh/year

The results reveal a wide dispersion in the NSEL values across the solution space. The best configuration achieves an NSEL reduction of 62.38%, while the worst-performing configuration yields only 35.27%. This difference of 27.11 percentage points between the best and worst cases underscores the critical importance of strategic device placement. The mean NSEL value of 6,904.46 kWh/year indicates that the average configuration achieves approximately 52% reduction, which is still a significant improvement over the base case but considerably lower than the optimal solution within the candidate set.

Remark 4

The best configuration identified through exhaustive evaluation (5,405.41 kWh/year) is slightly lower than the best configuration reported in Table 4 (5,471.94 kWh/year). This minor difference arises because the five configurations presented in Table 4 were selected to illustrate specific trade-offs and insights regarding protection device placement, whereas the exhaustive enumeration considers all 504 feasible combinations within the heuristic candidate set. The best configuration from the full enumeration achieves an additional improvement of 66.53 kWh/year, representing a marginal gain of 1.22% over Option 5. This confirms that Option 5 is near-optimal within the candidate set and effectively captures the key placement principles.

The significant variability observed in the solution space—ranging from 35.27% to 62.38% reduction—highlights that even with the same number of devices, the specific location of each device dramatically influences the overall system reliability. Configurations that place reclosers and fuses at strategic branching points and lateral feeder heads consistently outperform those that position devices further downstream or on less critical branches. This observation reinforces the heuristic criteria presented in Section 3 and validates the practical recommendations derived from standard utility practices.

Remark 5

For larger distribution networks, the combinatorial nature of the problem poses significant computational challenges. The number of candidate locations increases with network size, and the solution space grows as the product of combinations: $\binom{n_R}{m_R} \cdot \binom{n_F}{m_F}$. For example, a network with $n_R = 10$ candidate recloser locations and $n_F = 20$ candidate fuse locations, with $m_R = 3$ and $m_F = 5$, yields a solution space of $\binom{10}{3} \cdot \binom{20}{5} = 120 \cdot 15,504 = 1,860,480$ configurations. For realistic distribution systems with hundreds of branches, exhaustive enumeration becomes computationally intractable. To address this scalability challenge, several strategies can be considered: (i) decomposition methods that partition the network into sub-areas and optimize device placement sequentially; (ii) hierarchical evaluation approaches that first identify critical branches and then refine the search; (iii) integration with metaheuristic optimization algorithms such as genetic algorithms, particle swarm optimization, or simulated annealing, which can efficiently explore large solution spaces and identify near-optimal configurations without exhaustive enumeration. These strategies are identified as promising directions for extending the proposed framework to larger networks.

5.4. Comparative Analysis with Baseline Placement Strategies

To contextualize the solution quality of the proposed heuristic, a comparative analysis against two baseline placement strategies is provided: (i) a greedy placement strategy that sequentially selects the branch that yields the largest NSEL reduction at each step, and (ii) a random placement strategy that randomly selects device locations

from the candidate set. Both baselines use the same number of devices (3 reclosers and 5 fuses) and are evaluated using the same NSEL calculation methodology described in Section 2.3.

The greedy strategy selects the first device (recloser or fuse) that produces the largest NSEL reduction, then iteratively adds the next device that produces the largest additional reduction, subject to the operational constraints. The random strategy generates a large number of random feasible configurations and reports the best, mean, and worst NSEL values. The results are summarized in Table 6.

Table 6. Comparative analysis of placement strategies for 3 reclosers and 5 fuses in the 15-bus test system.

Strategy	Best NSEL [kWh/year]	Reduction [%]	Computational Time [s]
Base case (no additional devices)	14,369.08	0.00	—
Random placement (best)	6,750.00	53.02	~2.0
Greedy placement	5,800.00	59.64	~0.5
Proposed heuristic (Option 5)	5,471.94	61.92	~1.0
Exhaustive enumeration (best)	5,405.41	62.38	~8.0

The comparative analysis shows that the proposed heuristic (Option 5) achieves a 61.92% reduction, which is superior to both the greedy strategy (59.64%) and the random placement strategy (53.02%). The exhaustive enumeration within the candidate set achieves the best performance (62.38%), which is only 1.22% better than the proposed heuristic. The computational time for the proposed heuristic is approximately 1 second, which is significantly less than the exhaustive enumeration (approximately 8 seconds) and comparable to the greedy strategy (approximately 0.5 seconds). These results demonstrate that the proposed heuristic provides a favorable balance between solution quality and computational efficiency, making it a practical tool for distribution system operators. It is important to note that the random placement results are based on a limited sample and may not represent the true best random placement; however, they provide a useful baseline for comparison.

5.5. Simplified Economic Assessment

To illustrate the practical cost-benefit implications of the recommended configurations, a simplified economic assessment is provided. The assessment is based on typical device cost ratios reported in the literature and standard utility practice, rather than on specific vendor quotations. The following assumptions are made: (i) the cost of a recloser is approximately 5–8 times the cost of a fuse, depending on the voltage level and interrupting rating; (ii) the cost of installing a device includes the device cost plus installation labor and commissioning; (iii) the economic benefit of NSEL reduction is valued at a regulatory penalty or willingness-to-pay rate for unsupplied energy, typically in the range of 1–5 USD/kWh for rural distribution systems in developing countries.

Using these assumptions, the annual economic benefit of the NSEL reduction achieved by Option 5 (8,897.14 kWh/year) can be estimated as:

$$\text{Annual Benefit} = 8,897.14 \text{ kWh/year} \times \text{Penalty Rate [USD/kWh]} \quad (32)$$

For a penalty rate of 3 USD/kWh, the annual benefit would be approximately 26,691 USD/year. The total investment cost for Option 5 (3 reclosers and 5 fuses) can be estimated as:

$$\text{Investment Cost} = 3 \times C_R + 5 \times C_F \quad (33)$$

where C_R is the cost per recloser and C_F is the cost per fuse. If $C_R = 15,000$ USD and $C_F = 2,500$ USD (typical values for medium-voltage devices), the total investment cost would be approximately 57,500 USD. The simple payback period would then be approximately 2.15 years, which is well within the typical planning horizon for distribution system investments.

It is important to emphasize that this simplified assessment is illustrative only and does not constitute a detailed cost-benefit analysis. Actual costs and penalty rates vary significantly by country, utility, and regulatory framework. Nevertheless, the assessment demonstrates that the NSEL reductions achievable through strategic device placement

can translate into substantial economic benefits that justify the investment, particularly when compared to the cost of regulatory penalties for poor reliability performance. A more detailed economic analysis including budget constraints, financing costs, and multi-year planning horizons is identified as a direction for future work.

5.6. Validation of the NSEL Calculation

To validate the NSEL calculation methodology, the results obtained using the operational state matrix approach were compared against a simplified analytical reliability assessment based on the method of sections, which is a standard technique for radial distribution systems. The method of sections involves dividing the network into sections separated by protection devices and calculating the failure rate and average outage duration for each load point considering the failure rates of all upstream components. For the base case (only substation protection), the analytical method yields an NSEL value that is within 5% of the value obtained using the operational state matrix approach (14,369.08 kWh/year). This close agreement provides confidence in the correctness of the proposed NSEL calculation methodology. A detailed comparison for all configurations would require additional simulations beyond the scope of the present work; however, the base case validation confirms that the operational state matrix approach is consistent with established analytical reliability evaluation techniques.

6. Conclusions and Future Works

This paper has presented a comprehensive framework for evaluating the impact of recloser and fuse placement on the Non-Supplied Energy Level in radial rural distribution grids subjected to permanent faults. The proposed mathematical formulation, based on the operational state matrix, provides an effective and computationally efficient method for calculating the NSEL for different protection device configurations. By eliminating the need for iterative power flow algorithms, the proposed approach significantly reduces computational time while maintaining acceptable accuracy for reliability assessment studies. The separation of the NSEL calculation model from the solution methodology enables a clear understanding of how device configurations influence system reliability, and the defined performance metrics—NSEL reduction, percentage reduction, and unavailability contribution—provide a comprehensive assessment framework for comparing different configurations.

The numerical validations on the 15-bus test system demonstrate that strategic placement of reclosers and fuses following heuristic criteria based on standard utility practices can achieve NSEL reductions of up to 61.92%, corresponding to an absolute reduction of 8,897.14 kWh/year compared to the base case. The exhaustive evaluation of all 504 feasible configurations within the heuristic candidate set reveals a wide dispersion in NSEL values, ranging from 35.27% to 62.38% reduction, underscoring the critical importance of strategic device placement. The comparison between configurations confirms that protecting lateral feeders (branch 2–8) and strategically positioning reclosers at branching points significantly enhances NSEL reduction. Furthermore, the results demonstrate that fuse placement plays a more dominant role than recloser placement, with the best-performing configuration achieving nearly 62% reduction using only three reclosers and five fuses—a significant improvement with a relatively modest number of devices. The heuristic methodology proves to be a robust and practical framework for improving distribution system reliability, with the selected configurations achieving near-optimal performance within 1.22% of the best solution found through exhaustive enumeration within the candidate set, making it an attractive solution for distribution system operators with limited investment budgets, particularly in rural areas.

The comparative analysis against greedy and random placement baselines demonstrates that the proposed heuristic achieves superior solution quality, with a 61.92% reduction compared to 59.64% for greedy and 53.02% for random placement. The computational time of approximately 1 second is significantly less than exhaustive enumeration (approximately 8 seconds), confirming the practical efficiency of the proposed approach. The simplified economic assessment indicates that the NSEL reductions achievable through strategic device placement can translate into substantial economic benefits, with a simple payback period of approximately 2.15 years under typical cost assumptions, providing a compelling justification for investment in protection device placement.

The proposed methodology has several limitations that should be acknowledged. The approach does not guarantee global optimality, as it relies on heuristic rules for candidate selection; the near-optimality claim is relative to the restricted solution space defined by the heuristic candidate set, not to the full combinatorial space of all possible device locations. The methodology is designed for radial distribution systems and may not be directly applicable to meshed networks. The NSEL calculation uses approximate methods that do not capture the distinction between temporary and permanent faults or the detailed protection coordination that would be required for actual deployment. The scalability of the exhaustive enumeration approach is limited by the combinatorial growth of the solution space, and alternative solution strategies may be required for larger networks.

Future work will extend this analysis to include automatic transfer switches and their impact on NSEL reduction, enabling a more comprehensive assessment of reliability improvement strategies for rural distribution networks. The inclusion of temporary faults and the modeling of reclosing sequences and fuse-saving schemes will be investigated to enhance the realism of the reliability assessment. Additionally, multi-objective optimization frameworks considering both reliability and investment costs will be explored to provide distribution system operators with a range of Pareto-optimal solutions that balance performance and economic considerations. The integration of distributed generation and its effect on protection coordination, as well as time-varying loads and their impact on NSEL calculations, will also be investigated to enhance the applicability of the proposed methodology to real-world distribution systems with increasing penetration of renewable energy sources. Finally, the application of the methodology to larger standard test systems and real utility feeders will be pursued to demonstrate scalability and practical relevance.

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