



Power Distribution System Reliability Analysis and Network Reconfiguration Using Pso Algorithm (A Case Study of Wolaita Sodo Town Distribution System)

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Abstract

The reliability analysis of a power distribution system is highly important for both customers and the utility to ensure supply continuity and improved revenue. With the growing demand for dependable power supply, it is crucial for utilities to dedicate efforts towards guaranteeing an uninterrupted power supply to meet customer needs. However, the frequent occurrence of power interruptions and the prolonged outage duration pose significant challenges to the power distribution systems, especially in Wolaita Sodo town, thus impacting the daily operations of customers. The three-year interruption data collected from Wolaita Sodo district revealed that the system average interruption duration index and system average interruption frequency index for the Wolaita Sodo town feeder are not within the EEU industry standard of 25hrs and 20 per year, respectively. According to the collected interruption data, the system average interruption duration index and system average interruption frequency index values are found as 573.59hrs and 427 per year in 2023, respectively. The unserved energy (EENS) is found to be about 1835.5MWh. This study focuses on improving the distribution system's reliability in Wolaita Sodo town through distribution network reconfiguration (DNR) based on automatic re-closers (AR) integration. The particle swarm optimization (PSO) in MATLAB is used to find the optimal locations of auto-reclosers (AR). The reliability indices such as system interruption frequency and duration and energy not served, are assessed using the ETAP simulation package. The study examined the reliability metrics by incorporating five auto-re-closure units with the help of particle swarm optimization for optimal location. The analysis revealed that with the



integration of five auto re-closure units, the system interruption frequency index is enhanced from 427 to 4 and the system interruption duration index is decreased from 573.59hr to around 54.03hr. Moreover, it was revealed from the results that the expected energy not served is reduced from 1835.5MWh to about 140.38 MWh per year, and the cost of unserved energy decreased from 992,454.85Birr to about 75,903.46Birr.

Keywords: Automatic re-closer, Distribution network reconfiguration, Failure analysis, PSO, Reliability index

I. INTRODUCTION

Radial feeders originate from distribution stations, serving clusters of customers without connecting to another feeder. Electricity travels through radial feeders from distribution to customers in an exclusive way, and any interruption in this way will result in a power outage for customers connected to those lines. Because radial supply lines are usually linked to only one substation and do not receive power from alternate sources, a fault at any particular node causes a complete shutdown of the downstream loads. Due to this, the reliability of the radial system is low.

Evaluation of distribution system reliability focuses on ensuring the availability and quality of power supply at every customer service entrance. Customer failure data analysis indicates that distribution system failures account for up to 90% of supply unavailability to a load, highlighting the critical importance of assessing the reliability of distribution systems. Basic indices must be calculated to evaluate the severity or significance of a system outage [1].

Improving power distribution system reliability is of utmost importance in ensuring uninterrupted electricity supply to consumers. By implementing advanced technologies, utilities can effectively monitor and manage their distribution networks. These technologies enable real-time monitoring of the grid, early detection of equipment failures, and quicker response times to outages. Through targeted investments in infrastructure upgrades and adopting best practices in maintenance processes, the reliability of power distribution systems can be significantly



enhanced, ultimately leading to a more resilient and efficient energy network for consumers [2].

By embracing innovative technologies and sustainable practices, the energy industry can build a more robust and efficient power distribution network that meets the evolving needs of consumers [3]. Investing in modernizing their infrastructure and adopting innovative solutions make utilities to better meet the growing demands for electricity while minimizing the risk of disruptions and enhancing overall grid resilience.

Improving the reliability of the distribution system is crucial in ensuring the consistent and uninterrupted flow of electricity to consumers. This entails implementing advanced monitoring and control technologies to detect faults or failures in the system promptly. By incorporating smart grid solutions, such as self-healing capabilities and real-time data analytics, utilities can proactively address issues before they escalate into widespread outages. Failure analysis and reliability improvement are crucial aspects in various fields, ranging from engineering and manufacturing to software development and business management. Here's why they are important [4]:

- *Identifying Weaknesses:* Failure analysis helps in identifying the weak points in a system, process, or product. By understanding why failures occur, engineers can address the root causes and make necessary improvements to prevent similar failures in the future.
- *Cost Reduction:* Failures can be costly, resulting in downtime, product recalls, warranty claims, and even legal liabilities. By conducting failure analysis and implementing reliability improvements, organizations can reduce the overall cost associated with failures and prevent financial losses.
- *Improving Safety:* In industries where safety is paramount, failure analysis plays a critical role in identifying potential hazards and improving safety measures. By addressing reliability issues, organizations can minimize the risk of accidents, injuries, and fatalities.
- *Optimizing Maintenance:* Understanding the causes of failures allows organizations to develop proactive maintenance strategies. By predicting when failures are likely to occur, companies can schedule maintenance activities more efficiently, reduce unplanned downtime, and extend the lifespan of equipment and assets.



- **Building Trust and Reputation:** Reliability and quality are key factors that influence customer trust and brand reputation. By continuously improving reliability through failure analysis, organizations can demonstrate their commitment to delivering reliable products and services, which enhances their reputation in the market. **Driving Innovation:** Failure analysis often leads to insights that drive innovation. By learning from failures, engineers can develop new technologies, materials, and methodologies that improve reliability and performance, driving continuous innovation and competitive advantage.

Using automatic re-closers (AR) for reliability improvement in electrical power systems offers numerous benefits, including reduced downtime, improved system reliability, enhanced grid resilience, efficient fault detection and localization, remote monitoring and control capabilities, optimized maintenance, and integration with smart grid technologies [5]. These implications contribute to a more robust and dependable electrical infrastructure, ensuring uninterrupted power supply to customers and supporting economic development and societal well-being.

The reliability of the system can be enhanced by decreasing the occurrence and length of defects. The primary approach to enhance power quality and reliability for end users is to swiftly clear faults and subsequently mitigate their impact on customers, should they arise. Numerous techniques, both electrical and non-electrical, have been proposed to enhance system reliability [5]:

- Non-electrical enhancement methods may include trimming of trees in the vicinity of overhead distribution lines, fitting animal protection on transformer parts, and organizing crews and considering human factors.
- Electrical enhancement methods encompass the installation of supplementary protective equipment such as fuse, re-closers, sectionalizing switches, reconfiguration, feeder reconnecting, and DGs,



Embracing a holistic approach to system reliability, which includes integrating RES will be key in building a resilient and sustainable power grid for the future. Ultimately, collective effort towards continuous improvement and adaptation will ensure that power distribution systems remain reliable, efficient, and secure in the face of changing demands and threats.

The distribution network is a key focus for research due to its customer appeal and efficient power delivery. In competitive markets, ensuring distribution reliability is crucial to meeting user satisfaction and maintaining reliable power supply standards. The distribution network reconfiguration (DNR) involves modifying the distribution network topology by adjusting the sectionalizing and tie switches as the load changes over time [6].

In distribution network reconfiguration, the selection of loops to be opened or closed plays a crucial role in achieving the desired optimization objectives. Loops are closed paths in the distribution network formed by interconnected branches (lines and transformers). By selectively opening or closing these loops, the network's configuration can be adjusted to improve various performance metrics such as reducing power losses, minimizing voltage deviations, or enhancing reliability. Here's how loops in the network reconfiguration are typically selected:

- i. Identification of Loops:** The first step is to identify the loops present in the distribution network. This is usually done through network modeling, where loops are identified based on the connectivity of network branches.
- ii. Evaluation of Loop Impact:** Each loop's impact on the network's performance metrics (reliability indices) is evaluated. This involves simulating the network with each loop individually closed or opened and assessing the resulting changes in network performance.
- iii. Optimization Algorithm:** Depending on the optimization objectives, an algorithm is selected to determine the optimal configuration of loops.
 - i. Objective Function:** An objective function is defined to quantify the desired optimization objectives, such as minimizing reliability indices. The objective function typically considers the impact of loop configurations on the metrics.



- iv. **Optimization Process:** The selected optimization algorithm is used to search for the configuration of loops that minimizes the objective function while satisfying any constraints (network topology constraints).
- v. **Evaluation and Validation:** The optimized loop configuration is evaluated through simulation and validation to ensure that it achieves the desired optimization objectives without violating any operational constraints. This involves simulating the network with the optimized loop configuration and analyzing its performance under various operating conditions and scenarios.

Overall, the selection of loops in distribution network reconfiguration involves a systematic process of evaluation, optimization, and validation to achieve the desired optimization objectives while ensuring the network's reliability and operational feasibility.

Ethiopian Electric Utility (EEU) has been striving to improve the delivery mechanism and enhance the quality of power supply to ensure both profitability and customer satisfaction. Despite these efforts, the power distribution system in Wolaita district has inadequacies in supplying the demanded power, lacking acceptable reliability indices and vulnerable to hazards for the public. Consequently, power interruptions have had diverse effects on vital infrastructure like industries, businesses, and residential consumers.

An outage refers to the condition of a component being unable to carry out its intended function due to a specific event directly linked to that element. Failures are typically categorized as either forced or scheduled, on the basis of their occurrence as a result of a feeder tripping or intentional turning off of the element for maintenance. The duration and nature of the outage determine whether it is permanent or temporary.

- **Temporary Forced Outages:** are caused by temporary factors, such as a tree branch touching a power line due to windy conditions. They last for less than 3 minutes. During these incidents, circuit breakers stay closed while relays are reset and lines are reclosed.
- **Permanent Outages:** refer to a disruption lasting more than 3 minutes before being resolved. Circuit breakers remain open throughout the duration of the outage.



The increased frequency of system failures has led to an increase in power outages. The reliability and stability of electricity supply are crucial for various industrial and service-oriented activities. Fluctuating power hinders productivity, damages equipment, and increases maintenance costs, which ultimately compromises product quality and damages the industry's reputation. The power interruption has resulted in production halts for customers and a lack of illumination in important areas of the town.

An automatic re-closer, also known as a circuit breaker with automatic reclosing capability, is a specialized electrical device used in power distribution systems to automatically interrupt and restore electrical power in the event of a temporary fault. It operates similarly to a traditional circuit breaker but includes additional features that enable it to automatically attempt to close the circuit after a predetermined time delay if a fault condition is detected.

The Wolaita Sodo-I substation transformer steps down the voltage to 132/15kV, 132/33 kV, and 132/66kV. The substation has four 15 kV-rated outgoing feeder lines and two 33 kV-rated feeders to supply the customers in Wolaita Sodo and surrounding towns in Wolaita zone. The one 66 kV-rated feeder supplies the power to the Gibe-III power plant for internal applications. The layout diagram of Wolaita Sodo substation is shown in Fig.1. As shown in the layout diagram, there are four feeders run at 15kV, two feeders at 33kV, and one at 66kV level.

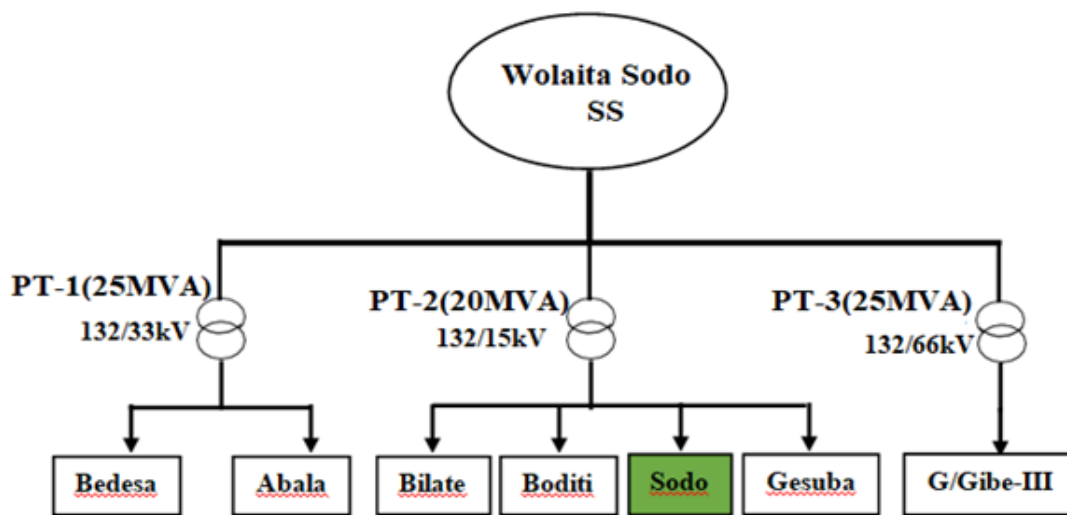


Fig. 1. Layout diagram of Wolaita Sodo substation



This research work examines a case study on the distribution network in Wolaita Sodo town, which is powered by the Wolaita Sodo old substation (PT-2) as shown in the layout diagram. It consists of 113 distribution transformers that are connected in a radial arrangement. The reliability indices, such as System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), and Average Service Unavailability Index (ASUI), are enhanced through DNR, implemented in MATLAB and ETAP software tools. The PSO algorithm is used to determine the optimal DNR points.

II. RESEARCH METHODOLOGY

A. Distribution System Modeling

Power distribution systems are typically modeled using various techniques and approaches to accurately represent their behavior, characteristics, and performance. Here are some common methods used for modeling power distribution systems:

- **Single-Line Diagrams (SLDs):** Single-line diagrams are simplified graphical representations of power distribution systems, showing the arrangement of components such as transformers, switches, circuit breakers, and loads. SLDs provide a high-level overview of the system topology and connectivity.
- **Load Flow Analysis:** Load flow analysis, also known as power flow analysis, is a mathematical method used to model and analyze the steady-state behavior of power distribution systems. It calculates the voltage, current, and power flow throughout the network under various operating conditions, considering factors such as load demand, generation, and system constraints. A backwards-forward sweep load flow method is used in this research.
- **Distribution System State Estimation:** Distribution system state estimation is a process that uses measurements from sensors and meters to estimate the operating conditions of power distribution systems, such as voltages, currents, and power flows. It helps utilities monitor and control distribution networks in real-time, optimize operations, and detect anomalies or equipment failures.



Power distribution systems are modeled using a combination of graphical, mathematical, and computational techniques to accurately represent their behavior and characteristics, support various analyses and simulations, and facilitate efficient and reliable operation.

The primary and secondary data necessary for the study were obtained from the district offices of EEU Wolaita Sodo. The collection process involved making physical observations in the network and main substations, and analyzing past recorded data on feeder loading (both peakload and load at each hour) for the substations. To determine the line impedance value, all the distances from one transformer to the next transformer are utilized, and based on the network modeling approach, the line impedance values are calculated according to the formula presented in the characteristic features of All- Aluminum Conductors (AAC) for different sizes presented in Appendix-A. In this case, the per-unit-length impedance is calculated at a frequency of 50Hz and a length of one kilometer [7].

Each conductor's flux linkage per unit length is given as [8]:

$$\lambda_A = \frac{\mu_0}{2\pi} I_A \ln \left(\frac{D}{GMR_a} \right) \text{wb/m} \quad (1)$$

The GMR value for three conductors is supposed to be the same and the total flux linkage expression is the same for all phases. Therefore, per-unit-length inductance for each phase becomes [8]:

$$L = \frac{\mu_0}{2\pi} \ln \left(\frac{D}{GMR_a} \right) \text{H/m} \quad (2)$$

Where $\mu_0 = 4\pi \cdot 10^{-7} \text{H/m}$

The inductive reactance per unit length is given by:

$$XL = 0.06283 \ln \left(\frac{D}{GMR_a} \right) \Omega/\text{km} \quad (3)$$

The impedance at a frequency of 50Hz is given by [8] [9]

$$Z_a = R_a + j0.06283 \ln \left(\frac{D}{GMR_a} \right) \Omega/\text{km} \quad (4)$$



Where D is the geometric mean distance (GMD) between phases and it is given as [8]:

$$D = \sqrt[3]{D_{ab} * D_{ac} * D_{bc}} \quad (5)$$

The minimum spacing between each of the phases, as stipulated in the EEU standard for a 15kV distribution system, is: $D_{ab}=0.64\text{m}$, $D_{bc}=0.51\text{m}$, $D_{ac}=1.15\text{m}$. Therefore, D can be found as about 0.72135m.

For stranded conductors, the GMR is given by:

$$GMR_a = K * r \quad (6)$$

Where, GMR_a : Geometric mean ratio of conductor a, K : GMR factor, r : actual conductor radius. The GMR factor for stranded conductors is given as shown in Appendix-B.

For the AAC-95 type conductors, the self-impedance is found as:

$$Z_a = 0.3085 + j0.32441\Omega/km$$

For the three-phase conductors, the impedance of each conductor is the same (i.e., $Z_a = Z_b = Z_c$). Then the positive sequence impedance of the conductors is obtained by multiplying the impedance per kilometer by its length.

In the same manner, impedance for AAC-50 and AAC-25 type conductors can be computed as:

$$\begin{aligned} Z_{50} &= 0.5785 + j0.34702\Omega/km \\ Z_{25} &= 1.1810 + j0.36940\Omega/k \end{aligned}$$

The per-unit resistance, reactance, nominal, and nominal diameter area of the feeders used are summarized in Appendix C.

The feeder in Wolaita Sodo town is linked to a total of 113 distribution transformers, which have a combined installed capacity of around 27MVA. The peak installed power demand of the town is about 12MW and 10.98MW. The distribution lines in the town consist of AAC95 and AAC50 type bare conductors, spanning a total length of approximately 56km. The layout of the proposed distribution system is depicted in Fig. 2. In Wolaita Sodo town, there are two feeders supplying



power to the town. For the purpose of this study, the focus is on the old feeder, as the new feeder exhibits more favorable reliability.

B. Reliability Modeling

Power distribution system reliability modeling involves assessing the ability of a distribution system to deliver power to customers continuously under normal operating conditions and during various contingencies or failure scenarios. Reliability modeling approach ranges from component level to system level. Some reliability modelling includes component reliability modelling, load modelling, fault modelling, outage modelling, reliability indices modelling, and probabilistic risk assessment. Modelling and sensitivity analysis.

By integrating these modelling approaches, utilities can gain insights into the reliability characteristics of their distribution systems, identify opportunities for improvement, and make informed decisions to enhance system reliability, resilience, and customer satisfaction. The evaluation of the indices defined by the IEEE enables the determination of the reliability of a distribution system. These indices are derived from load-point and system indices. Load-point indices are computed by analyzing the failure rates of components arranged in parallel and series.

On the other hand, system indices are calculated by considering the interruption frequency and duration for all customers connected to the system [9].

Average failure rate at load point i , λ_i (failures per year):

$$\lambda_{sys} = \sum \lambda_K \quad (7)$$

Where λ_k is the average failure rate

Annual outage duration at load point i , $U_{sys,i}$ (hours per year):

$$U_{sys,i} = \sum \lambda_K r_K \quad (8)$$

Where r_k is the failure duration at load point i due to failed element

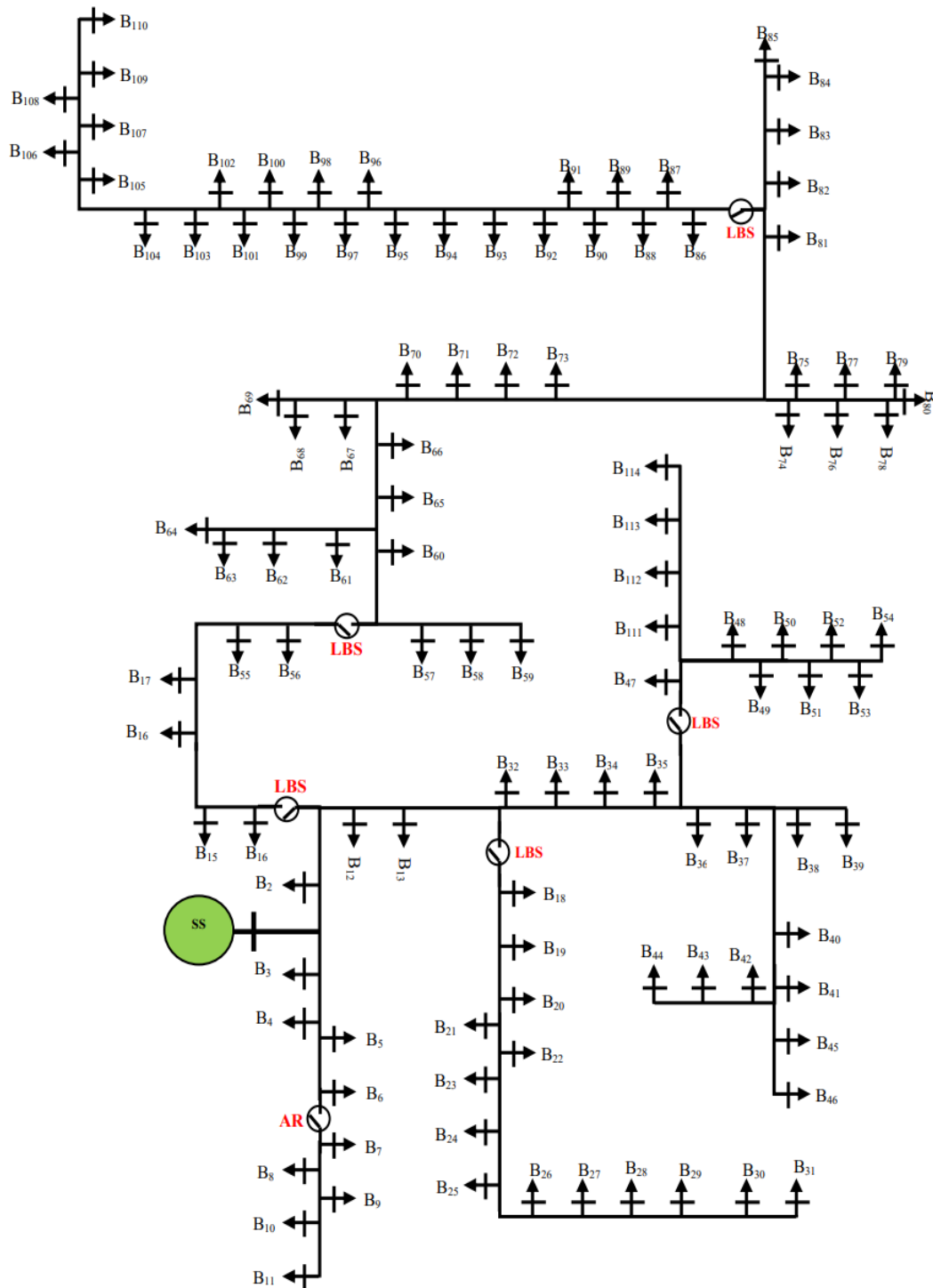


Fig. 2. Single-line diagram of Wolaita Sodo town distribution system

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Average outage duration at load point i , r_i (hours):

$$r_{sys,i} = \frac{U_{sys,i}}{\lambda_{sys,i}} = \frac{\sum \lambda_K r_K}{\sum \lambda_K} \quad (9)$$

Where λ_s , r_{sys} and U_{sys} are usually considered as basic indices required to evaluate distribution system reliability.

Expected Interruption Cost Index at load point, $ECOST_i$ is given by:

$$ECOST(i) = P_i \sum_j N_e \lambda_{e,j} * f(r_{ij}) \quad (10)$$

Where P_i is the load of the point i .

The SAIDI (Hr/ year) is a measure of the average length of time that customers experience power interruptions. The SAIDI can be given by:

$$SAIDI = \frac{\sum \text{Customer interruption durations}}{\text{Total number of customer served}} \quad (11)$$

The SAIFI represents the average number of interruptions per customer per year in a specific electricity supply system. The SAIFI can be given by:

$$SAIFI = \frac{\sum \text{Total number of customer interruptions}}{\text{Total number of customers served}} \quad (12)$$

The SAIFI represents the number of sustained interruptions an average customer will face annually. To enhance SAIFI, the focus should be on minimizing the occurrences of sustained interruptions. On the other hand, SAIDI measures the total interruption hours experienced by an average customer in a year. By utilizing the recorded Mega Watt (MW) load prior to each interruption, the SAIDI and SAIFI data can be utilized to determine the amount of unsold energy (MWH).

The Expected Energy Not Supplied Index, $EENS_i$ (MWh per year), is given by:



$$EENS_i = L_i * U_{sys} \quad (13)$$

The average tariff value of approximately 0.5407 is derived from the combined first-block tariffs applicable to both domestic and commercial customers, representing the assumed grouping of the majority of Ethiopian electricity consumers [10]. The yearly unsold energy cost due to the interruptions happening on a feeder in the substation can also be calculated as:

$$EENS(cost) = \sum L_i * U_{sys} * 0.54 \quad (14)$$

Where L_i is the load recorded from the relay at the substation in the nearest hour before event i

In a simpler way, the interruption cost can be calculated by using the EENS (since it is the product of the load before interruption and its duration) and the average tariff per kWh. The EENS is collected, and the interruption cost is calculated as per the recommended formula and presented for the Wolaita Sodo town feeder.

The Customer Average Interruption Duration Index (CAIDI) represents the average duration required to restore service to an average customer during a sustained interruption. It is calculated by dividing the total duration of customer interruptions by the total number of interruptions. The CAIDI can be given by:

$$CAIDI = \frac{\sum \text{Customer interruptions Duration}}{\text{Total number of customers Interruptions}} \quad (15)$$

The CAIDI quantifies the duration of an average outage and serves as an indicator of the utility's responsiveness to system disruptions. Enhancing CAIDI involves minimizing outage durations, yet it can also decrease with an increase in brief interruptions. Therefore, a decrease in CAIDI may not always indicate enhanced reliability.

The average service availability index (ASAI) that represents the availability of the supply to the customers can be given by:

$$ASAI = \frac{\sum \text{Customer Service availability hours}}{\text{Customer Service availability demand hours}} \quad (16)$$

The ASAI is the customer-weighted availability of the system and provides the same information as SAIDI. Higher ASAI values reflect higher levels of system reliability.



C. PSO Algorithm for DN

The particle swarm optimization (PSO) is one of the swarm intelligence algorithms introduced by J. Kennedy and E. Russell from social animal characters and the concept of schooling fish and flocking birds [11]. Due to its ease of implementation, highly precise solutions, and fast convergence, PSO has gained significant popularity in solving practical problems. PSO is related to other swarm intelligence algorithms (SIA) such as ant colony optimization (ACO), and it shares many similarities with evolutionary computation techniques like genetic algorithms (GA) [12].

The PSO system begins with a population of random solutions and proceeds to search for the optimal solution by updating generations. Unlike GA, PSO does not employ evolution operators like crossover and mutation. Instead, in PSO, particles navigate through the problem space by tracking the current optimal particles. The PSO principle involves modifying the velocity (accelerating) of each particle towards its personal best (p_{best}) and global best (g_{best}) positions at every time step. The acceleration is determined by a random factor, with distinct random numbers generated for acceleration towards p_{best} and g_{best} positions.

Every particle maintains a record of its coordinates in the problem space, which are linked to the best solution (fitness) it has attained up to that point. This particular value is referred to as the personal best (p_{best}). Additionally, the PSO algorithm keeps track of another "best" value, which is the best value achieved by any particle in the neighborhood of the current particle. In case where a particle considers the entire population as its topological neighbors, the best value becomes a global best and is known as the global best (g_{best}).

The two main equations of the PSO algorithm [particle's velocity (V) and location (x)] can be expressed as [11]:

$$\left. \begin{aligned} V_i(t+1) &= w * V_{ij}(t) + r_1 r_1 P_{ij}(t) - x_{ij}(t) + r_2 c_2 g(t) - x_{ij}(t) \\ X_i(t+1) &= V_{i(t+1)} + X_i(t) \end{aligned} \right\} \quad (17)$$

Where r_1 and r_2 are random numbers uniformly distributed in the range of 0 to 1.

The PSO algorithm has a number of parameters that need to be fixed. One of the parameters is the size of the population. This is set empirically based on the dimensionality and perceived difficulty of



a problem. Values in the range 20 to 50 are quite common. The parameters c_1 and c_2 , commonly called acceleration coefficients, are used to determine the magnitude of the random forces in the direction of personal best and neighborhood best. The value $c_1 = c_2 = 2.0$ is adopted in early PSO research. The number in PSO algorithm is important to get better result. A too low number of iterations may stop the search process prematurely, while too large iterations have the consequence of unnecessary added computational complexity and more time needed [12]. The particle is a random number that could result in the optimal value of the required fitness (objective) function. In our case, the particle represents the switch that could result in the optimal fitness function value (SAIFI, SAIDI and EENS).

The position is initialized randomly and the particle should start from a random position (i.e., a random bus number) in the system. The particle must move within the search space within the buses. The personal best is the resulting individual particle fitness value and the global best is the best fitness value compared to other particles' fitness values. The objective is to find the optimal DNR points that result in the minimum reliability indices. Doing this, the control variables should not be violated, meaning that they should be within the acceptable ranges and the considered constraints should not be violated. The velocity of the particle represents the moving force of the particle (random fitness function value) from one candidate bus to the next bus in order to find the optimal values.

The weights represent that each candidate fitness solution should be weighted respectively to the neighbor particle fitness. The general flow chart of the proposed PSO is shown in Fig. 3.

D. Objective Function Formulation

Considering the reliability optimization problem, the objective function that needs to be optimized is as follows:

$$F = w1 * \frac{SAIFI}{SAIFI_t} + w2 \frac{SAIDI}{SAIDI_t} + w3 \frac{EENS}{EENS_t} \quad (18)$$

The aim is to minimize the objective function while adhering to the constraints, in order to achieve optimal values for the failure rate and repair time in every section of the distribution systems.



a) Conditions governing the decision variables (Constraints)

$$\left. \begin{array}{l} \lambda k_{min} \leq \lambda k \leq \lambda k_{max} \\ rk_{min} \leq \lambda k \leq rk_{max} \end{array} \right\} \quad (19)$$

Where $k=1: N_c$

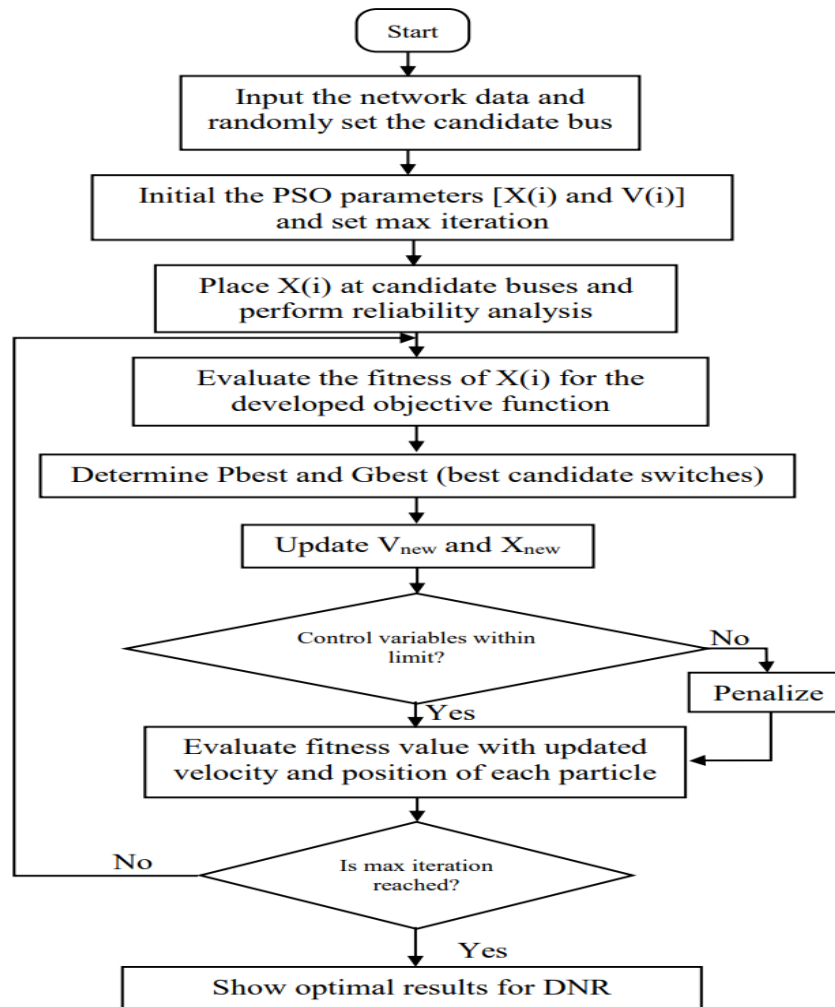


Fig. 3. Flow chart for the PSO algorithm

The average failure rate and repair time of the k th section are denoted as λ_k and r_k , respectively. On the other hand, $\lambda_{k,min}$ and $r_{k,min}$ represent the minimum reachable values for the failure rate and repair time of the k^{th} section. Additionally, $\lambda_{k,max}$ and $r_{k,max}$ indicate the maximum allowable failure rate and repair time, respectively. SAIFIt, SAIDIt, and AENSt are the target values for respective indices.



III. RESULTS AND DISCUSSIONS

A. Causes of Power Interruption in Wolaita Sodo Town

To enhance reliability, it is essential to pinpoint the specific type of fault on the distribution system that has the most significant impact on system reliability. Analyzing data gathered from the feeder, including the total frequency and duration of outages for each fault type annually, allows for the compilation of numerical values presented in Tables 4, 5, and 6.

The causes are classified into distribution permanent earth fault (DPEF), distribution permanent short circuit (DPSC), operational case (OP) and others. Here, faults having small frequency and duration (distribution temporary earth fault (DTEF), distribution temporary short circuit (DTSC) and distribution line overloading (DLOL) are grouped into others. The outages related to OP cases are due to system maintenance, new transformer erection, outages due to commands from the national load dispatch center for peak load periods, or periodic inspection of the system. Outage frequency and duration data of Wolaita Sodo town for the years 2021 to 2023 are given in Appendix-D through Appendix-F

As shown in Table Appendix-D, regarding the duration, the main causes of power interruptions in the town are DPSC, DPEF and OP cases, having annual averages of 247.63 Hrs, 246.94 Hrs, and 155.47 Hrs, respectively. The total annual interruption frequency and duration for the year 2021 are found to be 603 and 658.45 Hrs, respectively.

The summary of interruption history of Wolaita Sodo town as of 2022 is shown in Appendix-E. The main causes of power interruptions in the town are DPEF, DPSC and OP cases having annual averages of 228.44 Hrs, 198.57 Hrs, and 134.85 Hrs, respectively. The total annual interruption frequency and duration for the year are found to be 479 and 565.93 Hrs, respectively.

Moreover, the power interruptions can be broadly classified into forced outages and planned outages. The forced outages consist of DPEF, DPSC, DTEF, DTSC and DLOL, while the planned outage is the power outage due to operational and maintenance cases.

The summary of interruption history of Wolaita Sodo town as of 2023 is shown in Appendix-F.



As shown in the table, regarding the duration, the main causes of power interruptions in the town are DPSC, OP and DPEF cases having annual averages of 201.26 Hrs, 198.83 Hrs, and 170.33 Hrs, respectively. The total annual interruption frequency and duration are found to be 427 and 573.59 Hrs, respectively. Summary of forced and planned outage duration (D) and frequency (F) of the study site is given in Appendix-G. As shown in the Table, the forced power outage case holds the higher portion than the planned power outage regarding frequency as well as duration of the interruptions. From a total interruption frequency of 603, 479 and 427 in 2021, 2022 and 2023, about 72.31%, 74.32% and 68.38% of interruptions, respectively, are due to forced outages on the feeder. For the past three years, the average of 71.67% of interruptions in Wolaita Sodo town is due to forced outage cases, and 28.33% of interruptions are due to planned outage causes. Regarding the interruption duration, an average of 72.63% of interruption durations are due to forced causes and 27.37% are due to planned cases.

Among the causes of forced outages, the analysis is conducted to find which fault is most common on the feeder. The numerical values of forced outage data are presented in Table I. As shown in the table, among forced power outage cases, the DPEF and DPSC seem to have the same percentage but DPSC has a little bit higher percentage than DPEF regarding frequency as well as duration of the interruptions.

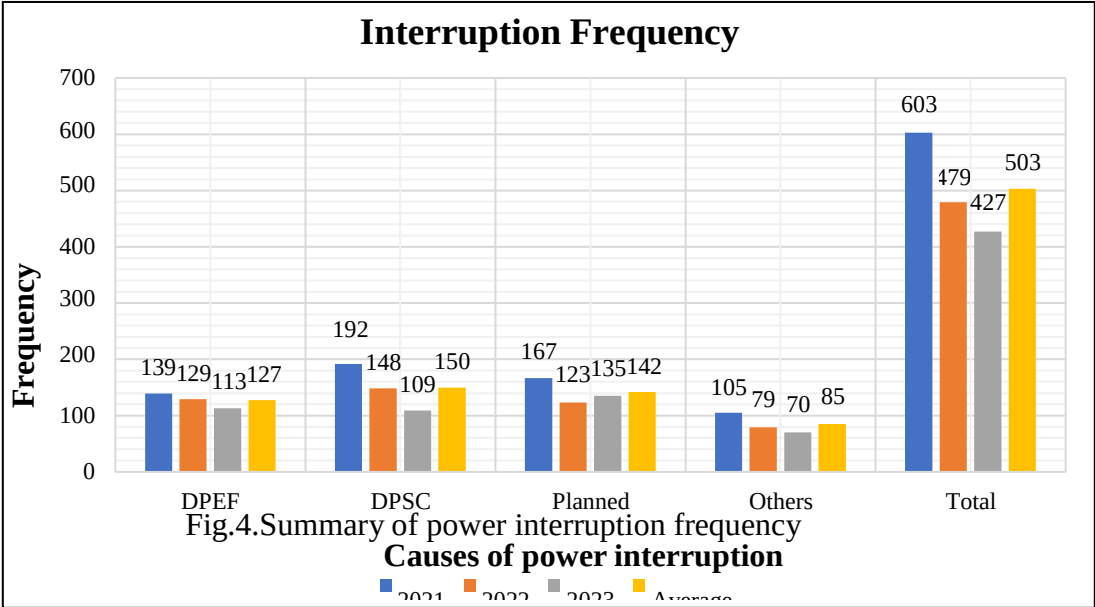
TABLE I

SUMMARY OF CAUSES OF FORCED OUTAGE DURATION (D) AND FREQUENCY (F)

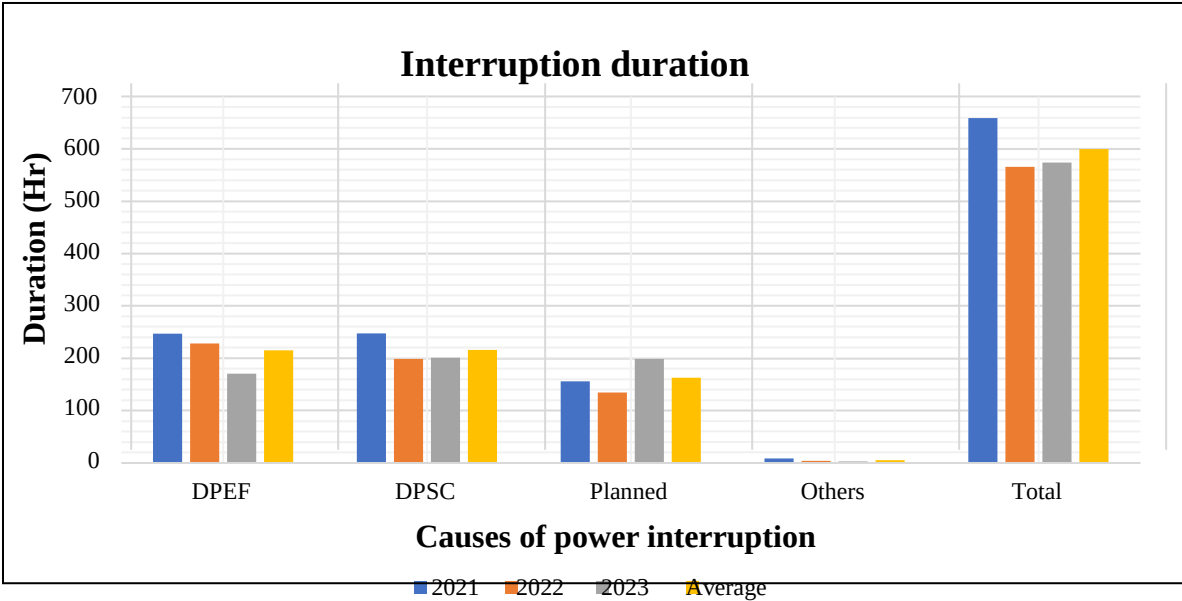
Year	Total		DPEF				DPSC				Others			
	F	D	F	D	%F	%D	F	D	%F	%D	F	D	%F	%D
2021	436	502.98	139	246.94	31.88	49.10	192	247.63	44.04	49.23	105	8.41	24.08	1.67
2022	356	431.08	129	228.44	36.24	52.99	148	198.57	41.57	46.06	79	4.07	22.19	0.94
2023	292	374.76	113	170.33	38.70	45.45	109	201.26	37.33	53.70	70	3.17	23.97	0.85
Average	361	436	127	215	36	49	150	216	41	50	85	5	23	1

For the past three years, an average of 41% of interruptions occurred in Wolaita Sodo town due to DPSC cases, and 36% of interruptions occurred due to DPEF causes. Regarding to the interruption duration, average of 50% interruption durations are due to DPSC and 49% are due to DPEF cases.

The summary of power interruption frequency and duration data of the Wolaita Sodo town power distribution system feeder for the past three years is shown in Fig .4 and Fig. 5 below, respectively



As shown in Fig.4, DPSC has a higher average interruption frequency than DPEF and the planned power interruption for the feeder. The planned power interruption ranks second regarding the interruption frequency for the three years.





As shown in Fig.5, DPSC and DPEF have almost the same average interruption duration for the three years, and this results in a higher percentage than the planned power interruption of the feeder.

B. Reliability Indices Evaluation without DNR

Based on the secondary data obtained from the district, the base case reliability indices analysis is presented under this section. The interruption data for a span of three years, including the frequency and duration of interruptions, is presented in Table II. As shown, the number of interruption occurrences in 2021, 2022 and 2023 is found to be about 603, 479 and 427, respectively. Thus, the existing system SAIFI is found to be 603, 479 and 427 for the respective years showing that the resulting values are very far away from the expected standard of 20.

TABLE II
THREE-YEAR ANNUAL INTERRUPTION DATA OF WOLAITA SODO TOWN FEEDER

Month	Frequency of interruptions			Duration of interruptions (Hr)		
	2021	2022	2023	2021	2022	2023
Annual	603	479	427	658.45	565.93	573.59

The annual duration of the interruptions in 2021, 2022 and 2023 is found as about 658.45Hrs, 565.93Hrs, and 573.59Hrs, respectively. Thus, the SAIDI for the existing distribution system is found as 658.45hrs, 565.93hrs and 573.59hrs in the respective years showing that the resulting values are very far away from the expected standard of 25hrs.

The reliability index values for the currently existing distribution system are summarized in Table III, representing the base case reliability values. It is evident from the Table III that the annual SAIFI and SAIDI of the proposed distribution network exceed the recommended national SAIFI and SAIDI standard EEU values of 20 and 25 hours, respectively.

TABLE III
EXISTING DISTRIBUTION SYSTEM RELIABILITY INDICES

Year	SAIFI	SAIDI (Hr)	EENS (MWh)	Ecost (Birr)	ASAI (%)
2021	603	658.45	2554.80	1,379,584.44	92.48
2022	479	565.93	2065.64	1,115,448.03	93.54
2023	427	573.59	1835.50	991,163.52	93.45



Based on the data presented in Table III, it is evident that the annual expected energy not supplied due to the interruptions is calculated based on the average active power before the interruption takes place. The EENS for the years 2021, 2022, and 2023 are approximately 2,554.80, 2065.64, and 1,835.50 MWh, respectively.

Utilizing these figures, the revenue that the EEU lost due to interruptions can be determined by taking into account the EENS for each year and the overall average tariff rate of 0.54Birr/kWh. In this manner, the interruption cost is found to be about 1.38 million Birr, 1.115 million Birr, and 0.99 million Birr in 2021, 2022 and 2023, respectively. Based on the available system interruption data, the average annual system availability for the years 2021, 2022, and 2023 is approximately 92.48%, 93.54%, and 93.45%, respectively.

The data regarding the monthly energy not supplied and its associated cost can be found in the section presented in a tabulated form in Fig. 6. As illustrated in Fig. 6, the data shows the maximum and minimum EENS values observed over the past three years, which are approximately 669.9MWh and 6.95MWh, respectively.

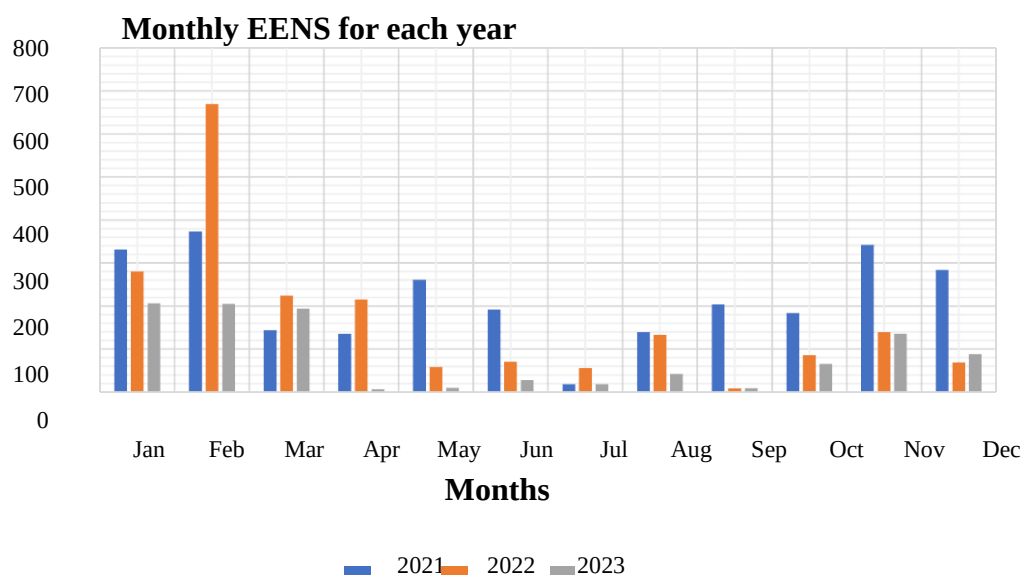


Fig. 6. Three-year monthly energy not supplied data

The data regarding the monthly energy not supplied and its corresponding cost are presented in



Fig. 7. From Fig. 7, it can be observed that the maximum lost revenue over the past three years amounts to approximately 295,200 Birr, while the minimum lost revenue is around 3,063 Birr.

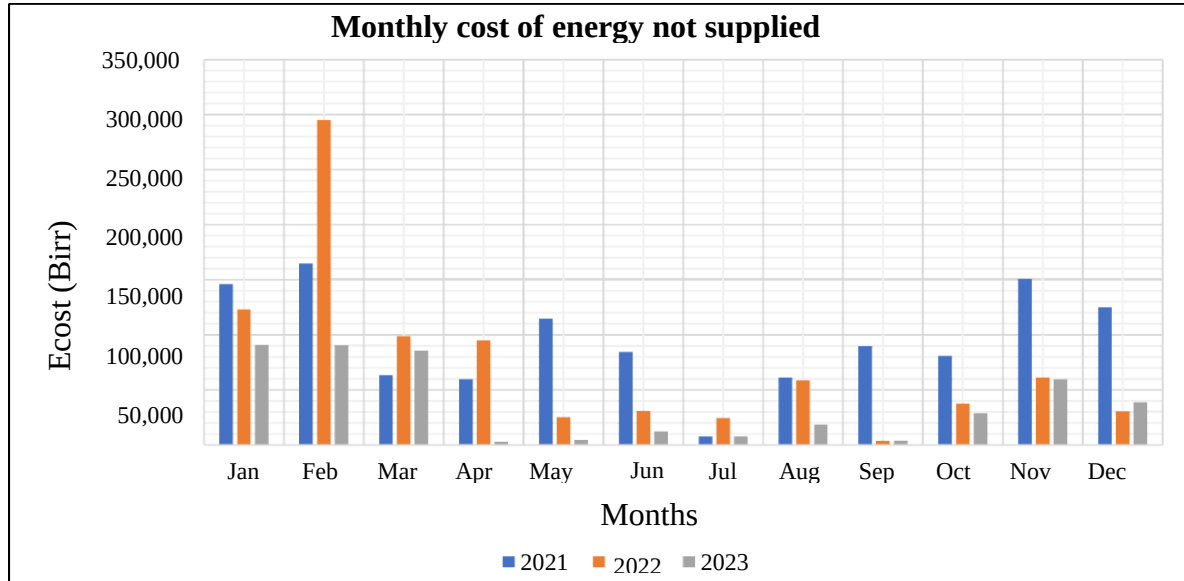


Fig. 7. Three-year energy not supplied cost due to interruption

C. Reliability Evaluation with DNR

For improvement of the system reliability through application of PSO-based DNR, the control parameter values of the PSO algorithm are given in Table IV. These values are adopted from the internationally accepted control values that could result in the required optimum. The number of iterations can be varied according to the simulation result. The number of dimensions represents the required number of tie-switches in the given loops within the system.

TABLE IV
PSO CONTROL PARAMETERS FOR DNR

Parameters	Values
Number of particles (birds)	10
Number of iterations	50
Acceleration coefficients (c_{max} and c_{min})	[2.2, 1.5]
PSO momentum (w_{max} and w_{min})	[1.2, 0.3]
Dimensions (DNR loops)	5
Initial tie switch points	[114 115 116 117 118]



The five initial tie switches considered are [114 115 116 117 and 118]. The load flow is conducted to determine the optimal network reconfiguration point.

TABLE V

INITIAL PROPOSED TIE SWITCHES CONSIDERED BEFORE DNR

No	From Bus	To Bus
114	13	31
115	39	54
116	17	69
117	70	94
118	98	110

Initially, the proposed distribution system is designed to have five meshed loops and the normally closed switches in each loop are presented as shown in Table VI. The number of tie switches in the system should not be greater than that of the number of meshed loops.

TABLE VI

INITIAL LOOPS AND NORMALLY CLOSED SWITCHES

Loop 1: 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 114
Loop 2: 35, 36, 37, 38, 46, 47, 48, 49, 50, 51, 52, 53, 115
Loop 3: 54, 55, 59, 64, 65, 66, 67, 68, 116
Loop 4: 70, 71, 72, 80, 85, 86, 87, 88, 89, 90, 91, 92, 93, 117
Loop 5: 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 118

The resulting candidate optimal DNR points are presented as shown in Table VII. As shown, the tie-switch combination of case three resulted in a better result than other combinations. As shown, scenario (case) three resulted in the SAIFI and SAIDI values of about 34 and 43.87hrs, respectively.

TABLE VII

OPTIMAL TIE-SWITCHES COMBINATIONS AND RELIABILITY

Cases	Tie-switches locations	SAIFI	SAIDI (hrs)
Initial	Without AR units as of 2023	427	573.59
1	28, 53, 68, 117, and 118	39	50.09
2	30, 66, 115, 117, and 118	42	63.4



3	27, 50, 66, 93, and 106	34	43.87
4	27, 68, 115, 117, and 118	36	47.92
5	27, 53, 68, 117, and 118	35	45.38

For improvement of the reliability through application of DNR, the system is required to be reconfigured first. The PSO algorithm utilized for the proposed network DNR is formulated by using the help of MATLAB and the optimal DNR points are found as shown in Table VII.

TABLE VIII
OPTIMAL DNR POINTS FOR RELIABILITY EVALUATION

#	NC opening switches			Tie-switch location		
	From bus	To bus	Length(m)	From bus	To bus	Length (m)
1	27	28	772.82	18	28	971.24
2	50	51	441.58	39	54	237.06
3	66	67	909.3	17	69	1027.12
4	93	94	483.93	69	94	508.39
5	106	107	204.37	98	110	604.03

Based on the result of the optimal auto re-closure (AR) location, the network is redesigned. The reconfigured network is shown in Fig. 8. After the optimal DNR has been applied in the system, the presentation of the power supply continuity possibility under each scenario and its performance is presented.

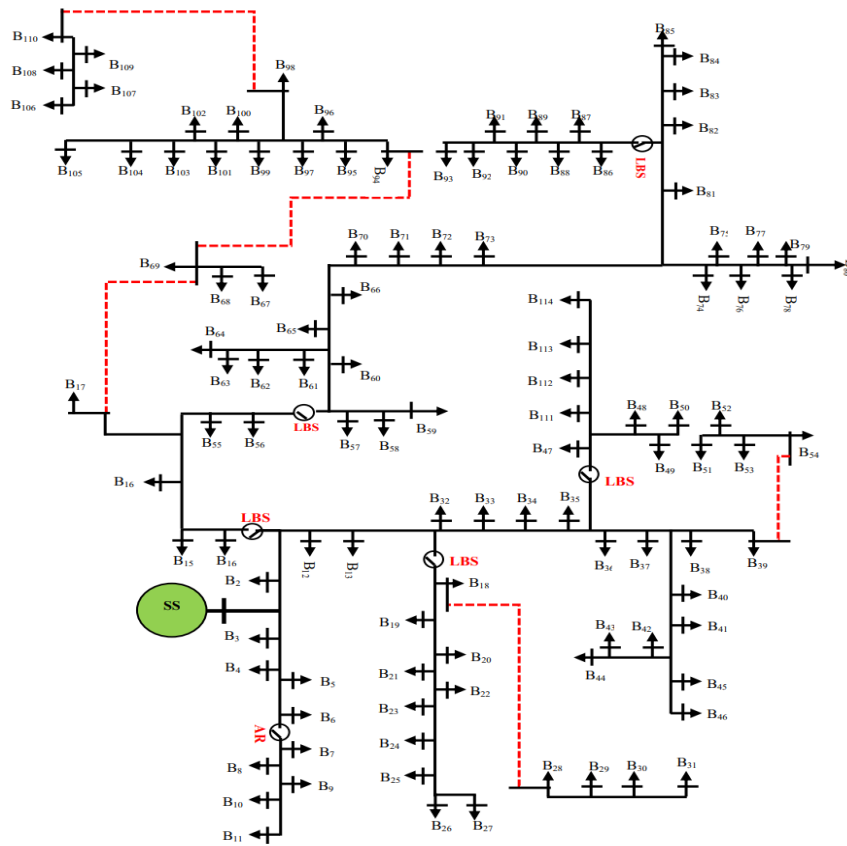


Fig. 8. Re-configured distribution network

The overall reliability analysis indices using ETAP software for different number of auto re-closer (AR) of the proposed system is shown in Table IX.

TABLE IX
RESULTING RELIABILITY INDICES UNDER DIFFERENT SCENARIOS

Year	SAIFI	SAIDI (Hr)	EENS (MWh)	Ecost (Birr)
2023	427	573.59	1835.5	992,454.85
One AR	203	211.57	677.02	366,064.71
Two AR	123	156.43	500.57	270,658.20
Three AR	62	86.74	277.68	150,141.57
Four AR	50	60.19	192.61	104,144.23
Five AR	4	54.03	140.38	75,903.46



If only the AR unit is used within the system:

- The SAIFI is decreased from 427 to 203; the SAIDI decreased from 573.59hrs to 211.57hrs. In other words, the customers in the town connected through this power distribution system can expect an average of 211.57hours of interruptions per year, with approximately 203 interruptions annually. The customers in the town could have about 8,548.43 hrs (97.58%) service availability annually. The estimated unserved energy is found as about 677.02MWh with an interrupted time energy cost of about 366,064.71Birr from this feeder alone annually.

If two AR units are used within the system:

- The SAIFI is decreased from 427 to 123; the SAIDI decreased from 573.59hrs to 156.43hrs. In other words, the customers in the town connected through this power distribution system can expect an average of 156.43hrs of interruptions per year, with approximately 123 interruptions annually. The customers in the town could have about 8,603.57hrs (98.2%) service availability annually. The estimated unserved energy is found as about 500.57MWh with an interrupted-time energy cost of about 270,658.2Birr from this feeder alone annually.

If three AR units are used within the system:

- The SAIFI is decreased from 427 to 62; the SAIDI decreased from 573.59hrs to 86.74hrs. In other words, the customers in the town connected through this power distribution system can expect an average of 86.74hrs of interruptions per year, with approximately 62 interruptions annually. The customers in the town could have about 8,673.26hrs (99.01%) service availability annually. The estimated unserved energy is found as about 277.68MWh with an interrupted-time energy cost of about 150,141.57 Birr from this feeder alone annually.

If four AR units are used within the system:

- The SAIFI is decreased from 427 to 50; the SAIDI decreased from 573.59hrs to 60.19hrs.



In other words, the customers in the town connected through this power distribution system can expect an average of 60.19hrs of interruptions per year, with approximately 50 interruptions annually. The customers in the town could have about 8,699.81hrs (99.3%) service availability annually. The estimated unserved energy is found as about 192.61MWh with an interrupted-time energy cost of about 104,144.23Birr from this feeder alone annually.

From the reliability analysis results, if five AR units are integrated within the distribution network, the resulting reliability can be summarized as follows:

- The number of interruptions (SAIFI) that would occur in the given distribution network could be decreased from 427 as of 2023 to about 4 annually. This means the customers in the town would lose the power supply about 4 times annually.
- The duration of interruptions (SAIDI) could be decreased from a base case of 573.59hr to about 54.03 Hrs. This means the customers in the town would lose the power supply for about 54.03hrs annually.
- The unserved energy (EENS) in the distribution network could be decreased from a base case value of 1835.5MWh to about 140.38MWh annually
- The cost of unserved energy (Ecost) that the utility would lose could be decreased from a base case value of 992,454.85Birr as of 2023 to about 75,903.46Birr (1380.063\$).

The SAIFI comparison is shown in Fig. 9. As shown, the number of interruptions is tremendous when more auto-reclosers (AR) is integrated in to the existing distribution network.

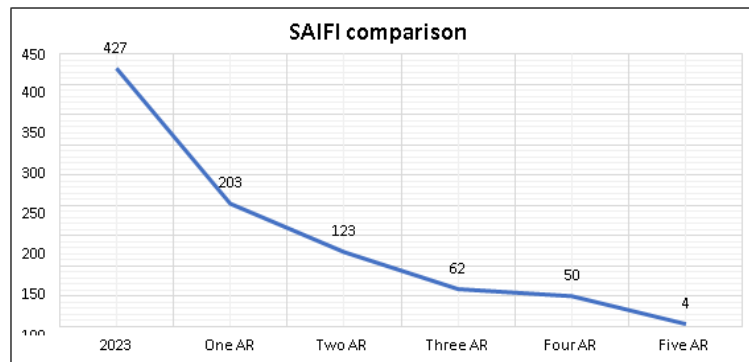


Fig.9. SAIFI evaluation for different auto re-closure (AR)



The SAIFI and SAIDI comparison before and after integration of auto re-closure is presented in Fig. 10. As shown, application of AR units within the distribution network significantly reduced each of the reliability indices compared to the base case initial values. As shown, the SAIFI and SAIDI values almost attained the EEU expected index values of 20 and 25hrs annually

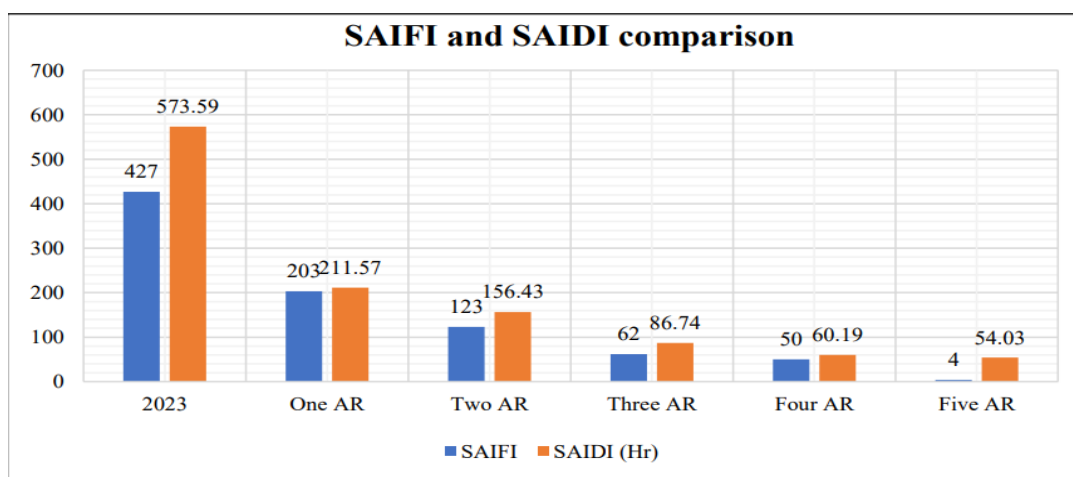


Fig.10. SAIFI and SAIDI evaluation with number of AR integration

The EENS and ECOST comparison is presented in Fig. 11. As shown, application of AR units within the distribution network significantly reduced each of the reliability indices compared to the base case initial values.

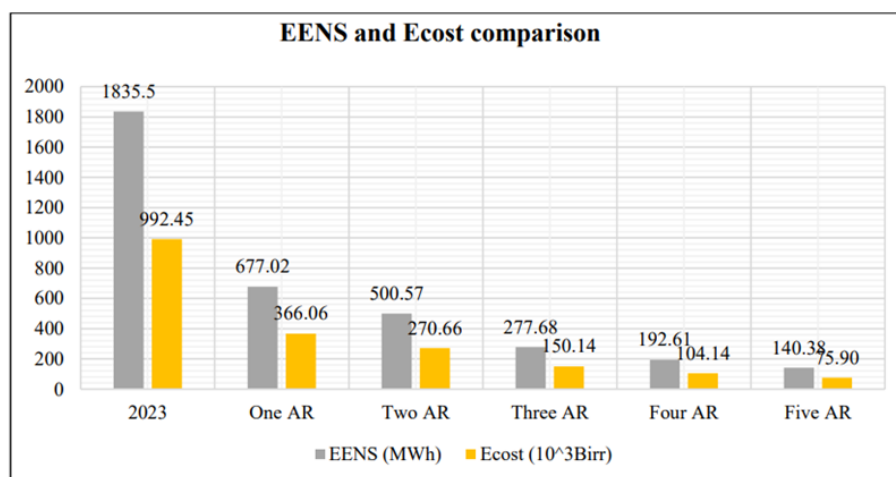


Fig.11. EENS and ECOST comparisons for different number of AR



IV. CONCLUSIONS AND RECOMMENDATIONS

Failure analysis and reliability improvement are integral components of quality management and risk mitigation strategies. By systematically analyzing failures, organizations can identify opportunities for improvement, enhance product quality, reduce costs, improve safety, and build trust with customers, ultimately driving long-term success and sustainability.

Using automatic re-closers for reliability improvement in electrical power systems offers numerous benefits, including reduced downtime, improved system reliability, enhanced grid resilience, efficient fault detection and localization, remote monitoring and control capabilities, optimized maintenance, and integration with smart grid technologies. These implications contribute to a more robust and dependable electrical infrastructure, ensuring uninterrupted power supply to customers and supporting economic development and societal well-being.

Data on network interruptions is gathered from the EEU Wolaita Sodo district. The research results indicate that the power distribution system in Wolaita Sodo town does not meet the standards set by the EEU at base case condition. According to the 2023 data, the feeder encountered an average of 427 interruptions annually, with each interruption lasting around 573.59 hours per year. The system consists of 113 distribution transformers and utilizes AAC50 and AAC95 rated bare conductors across the network. The town's distribution network base power and voltage are set at 20MVA and 15kV, respectively. The DNR aimed to enhance the reliability of the system. The PSO method is utilized to determine the optimal locations for placing the AR units. By applying PSO, the AR unit's locations are efficiently determined, and subsequently, the system reliability indices are calculated.

The study examined the reliability metrics when incorporating five AR units in the system. The analysis revealed that with five auto re-closure units, SAIFI can be dropped from 427 to 4, SAIDI decreased from 573.59hr to around 54.03hr, EENS reduced from 1835.5MWh to about 140.38MWh per year, and the cost of unserved energy could be lowered from 992,454.85Birr to about 75,903.46Birr. Based on the study results, it is recommended that Ethiopian Electric Utility (EEU) should integrate the PSO-based automatic reclosure to improve the reliability indices and energy not served values of the Wolaita Sodo old 15kV feeder.



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Appendix A: Standard AAC Bare Conductor Characteristic Data

Parameters	Size-95	Size-50	Size-25
Normal Size (mm ²)	95	50	25
Average Cross Section (mm ²)	93.27	49.48	24.2
Stranding (Nos / mm)	19/2.5	7/3.0	7/2.1
Total Diameter (mm)	12.5	9.0	6.3
True diameter (mm)	10.8975	7.9377	5.56
Modules of Elasticity (kN/mm ²)	57	60	60
Ultimate Tensile Strength (kN)	15.68	7.94	5.78
Resistance at 20°C (ohm/km)	0.3095	0.5786	1.181
Maximum ampacity, at 35°C(Amps)	324	219	145
Maximum ampacity, at 50°C(Amps)	245	168	105

Appendix B: No. of Strands and GMR Factor for AAC Conductor

Strands	GMR factor, k	Strands	GMR factor, k
1	0.7788	19	0.7577
3	0.6778	37	0.7678
7	0.7256	61	0.7722

Appendix C: Distribution Line Parameters

Anom (mm ²)	Aact (mm ²)	Dstrnd (mm)	Dover (mm)	Dact (mm)	GMR (mm)	R (Ω/km)	X (Ω/km)
25	24.2	7/2.1	6.3	5.56	1.88	1.181	0.3694
50	49.5	7/3.0	9	7.9377	2.88	0.5785	0.34702
95	93.5	19/2.5	12.5	10.8975	4.129	0.3085	0.32441

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**Appendix-D:** Summary of Feeder Interruption Frequency and Duration as of 2021

Month	Causes for Interruption for 2021									
	DPEF		DPSC		OP		Others		Total	
Name	F	D(Hr)	F	D(Hr)	F	D(Hr)	F	D(Hr)	F	D
Jan	4	18.49	10	10.07	16	56.37	8	1.05	38	85.98
Feb	3	24.65	9	7.31	12	33.35	2	0.66	26	65.97
March	2	3.01	15	38.09	3	0.48	5	0.66	25	42.24
April	5	10.14	17	16.35	17	6.56	10	0.51	49	33.56
May	9	17.11	23	35.6	21	19.63	10	1.1	63	73.44
June	15	16.39	19	25.93	17	14.64	15	1.12	66	58.08
July	12	6.06	4	1.07	3	1.07	11	0.49	30	8.69
Aug	8	20.08	15	13.09	10	2.08	10	0.48	43	35.73
Sept	20	28.04	20	8.06	26	6.14	28	2.08	94	44.32
Oct	23	38.08	21	2.09	13	4.07	2	0.09	59	44.33
Nov	29	56.09	22	29.09	14	6.08	1	0.04	66	91.3
Dec	9	8.8	17	60.88	15	5	3	0.13	44	74.81
Total	139	246.94	192	247.63	167	155.47	105	8.41	603	658.45

Appendix-E: Summary of Feeder Interruption Frequency and Duration as of 2022

Month Name	Causes for Interruption for 2022									
	DPEF		DPSC		OP		Others		Total	
	F	D(Hr)	F	D(Hr)	F	D(Hr)	F	D(Hr)	F	D(Hr)
Jan	3	25.52	11	33.19	9	10.26	7	0.54	30	69.51
Feb	23	61.33	37	56.89	21	10.21	13	0.64	94	129.07
March	14	27.21	14	16.09	14	23.08	14	0.77	56	67.15
April	15	22.19	23	18.55	14	16.06	5	0.23	57	57.03
May	5	8.38	10	4.53	7	14.58	3	0.11	25	27.6
June	7	8.29	14	4.19	10	13.03	7	0.28	38	25.79
July	22	8.22	10	5.18	8	3.28	14	0.57	54	17.25
Aug	12	10.83	10	14.46	18	16.27	2	0.09	42	41.65
Sept	2	0.2	1	0.32	5	6.04	4	0.17	12	6.73
Oct	6	3.28	8	22.23	9	8.69	1	0.04	24	34.24
Nov	14	31.43	9	22.56	2	1.31	8	0.6	33	55.9
Dec	6	21.56	1	0.38	6	12.04	1	0.03	14	34.01
Total	129	228.44	148	198.57	123	134.85	79	4.07	479	565.93

**Appendix-F:** Summary of Feeder Interruption Frequency and Duration as of 2023

Month Name	Causes for Interruption for 2023									
	DPEF		DPSC		OP		Others		Total	
	F	D(Hr)	F	D(Hr)	F	D(Hr)	F	D(Hr)	F	D(Hr)
Jan	15	20.61	18	44.69	9	12.63	10	0.47	52	78.4
Feb	9	39.05	17	54.23	3	6.59	9	0.44	38	100.31
March	14	34.45	20	57.11	7	11.86	11	0.52	52	103.94
April	3	3.59	3	1.01	3	4.49	1	0.03	10	9.12
May	2	0.56	3	1.36	11	13.11	0	0	16	15.03
June	6	3.22	6	7.02	10	12.27	2	0.05	24	22.56
July	12	6.06	4	1.07	3	4.07	11	0.49	30	11.69
Aug	5	3.08	7	5.21	19	30.26	7	0.31	38	38.86
Sept	3	1.36	6	2.26	4	11.27	0	0	13	14.89
Oct	13	7.34	9	5.05	29	30.06	3	0.07	54	42.52
Nov	17	33.01	7	13.34	16	29.09	10	0.53	50	75.97
Dec	14	18	9	8.91	21	33.13	6	0.26	50	60.30
Total	113	170.33	109	201.26	135	198.83	70	3.17	427	573.59

Appendix-G: Summary of Forced and Planned Interruption Frequency and Duration from 2021 to 2023

Year	Total Interruption		Forced				Planned			
	F	D	F	D	%F	%D	F	D	%F	%D
2021	603	658.45	436	502.98	72.31	76.39	167	155.47	27.69	23.61
2022	479	565.93	356	431.08	74.32	76.17	123	134.85	25.68	23.83
2023	427	573.59	292	374.76	68.38	65.34	135	198.83	31.62	34.66
Average	503	599.32	361	436.27	71.67	72.63	142	163.05	28.33	27.37