Assessment and Enhancement of Distribution System Reliability by Renewable Energy Sources and Energy Storage

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Abstract

Distribution reliability mainly relates to the equipment outages and customer interruptions. In this work, authors attempt to identify the causes of power interruptions and customer's dissatisfaction. Additionally, the authors discuss design, maintenance, reliability and operation of Hawassa distribution feeder number 10, Ethiopia. Reliability worth is highly significant in power system planning and operation. A distributed generation (DG) ensures reliability improvement and it is used to increase the reliability worth. Hence in this work authors present the study of a radial distribution system and illustrate the impact of placing DG (solar photovoltaic (PV), wind turbine (WT)) and battery energy storage on the reliability worth. The reliability improvement is measured by different reliability indices that include SAIDI, CAIDI, EENS and ASAI. The analyzed and calculated distribution reliability indices values have been compared with standard benchmark values. Additionally, authors evaluate reliability of distribution networks by including islanded micro grid cases. The network includes two types of DG sources (PV, WT) and energy

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storage as back up. The distributed generators contribute to supply fraction of the load during grid-connected mode, but supply the heavy loaded area during islanded micro grid operation. The studies performed are supported with the Power Management System Software ETAP.

Keywords: Renewable energy sources, Battery energy storage, Reliability indices, Electrical Transient Analyzer Program (ETAP).

Abbreviations

AENS	Average Energy Not Supplied Index
ANSI	American National Standards Institute
ASAI	Average Service Availability Index
ASUI	Average Service Unavailability Index
BES	Battery Energy Storage
CAIDI	Customer Average Interruption Duration Index
CAIFI	Customer Average Interruption Frequency Index
DG	Distributed Generation
ENS	Energy not supplied
HRC	High Rupturing Capacity
IEC	International Electro technical Commission
kVAR	Kilovolt Ampere Reactive
kVA	Kilovolt Ampere
MW	Mega watt
MVA	Mega volt ampere
PV	Photo Voltaic
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SOL	System over load
WTG	Wing Turbine Generator

1 Introduction

In recent years, a number of studies are conducted in the field of power systems engineering with a great interest to implement renewable energy resources in power networks. The interest is motivated by environmental issues and rising fossil fuel prices. Since greenhouse gas emissions are the main cause of global warming, using technologies that do not produce greenhouse gas emissions would naturally eliminate their effects. Rising fossil fuel prices made the

renewable resources more competitive and encourage technologies to compete in the power market. For example, plug-in hybrid electric vehicles that are predicted to reshape the transportation future could interact with power grids as a means of energy storage. Alternative energy can be used to supply these vehicles, and this would reduce the dependency on fossil fuels. Distributed energy sources are such as wind, solar, geothermal etc.

Power quality is a great concern in electric distribution system. Customers require high quality service for more sensitive electrical and electronic equipments. The effectiveness of a power distribution system is measured in terms of efficiency, reliability and service quality. Currently, the Ethiopian Electric Power Corporation has 400 kV, 230 kV and 132 kV as primary transmission systems and 66 kV, 45 kV as sub transmission system. Further, 33 kV and 15 kV as distribution system. For 66 kV and 45 kV substations, the power transformers of various ratings like 25/12/6.3/3 MVA are installed to step down the voltage at 15 kV for distribution system. Mostly, at 33 kV and 15 kV overhead conductors are used for supplying distribution transformers. The voltage is then further stepped down by distribution transformers for domestic users. In the context of Ethiopia, electric power interruption has become a daily event. Also power interruption occurs at both low and medium voltage distribution level. The voltage fluctuation at the residential loads is a main reason for early failure of equipment, blackening of bulbs and decreased efficiency of domestic appliances.

Power system reliability assessment is primarily focused on the analysis of the healthy and failure states of a power system. Power system reliability can be subdivided in to two classes. Adequacy assessment takes into account the computation of sufficient facilities within the systems, satisfy the customer load and static conditions in the power system. Power system security has the goal to respond to disturbance arising within the system and therefore, deals with the dynamic conditions in the system. A power system is a complex network, highly integrated and very large. The reliability evaluation of the entire configuration at a time is complex, if it considers the power systems as an entire entity. Despite the evaluation complexity, the need for reliability assessment is ever increasing and more utilities are investing time in reliability analysis. Thus, to reduce the complexity of an overall power system, there are methodologies that divide whole power system into three functional zones. The first is generation facility and its ability to satisfy the system demand; the second is composite generation and transmission systems and its ability to deliver energy to the bulk power points; finally the third refers to the complete system including the distribution to satisfy the individual costumer's demand [1].

To meet customer demand, the power utility should be evolved and the distribution system should be upgraded, operated and maintained accordingly [2]. Energy losses in distribution systems are normally estimated rather than measured based on some thumb rule. In [3], a joint investigation is undertaken in association with a local utility to study this issue. Based on the data collected from feeders, true losses in primary and secondary feeders are obtained. The measured values by two new schemes for estimating losses are used to highlight the reliability of the system. In [2], authors provide a framework of a predictive, condition-based, and cost effective maintenance optimization program for transmission and distribution systems. In [4], the results of a power quality survey in a distribution system are presented and discussed. Further, power quality indices are calculated, which are based on IEEE and IEC Standards. In [5], the authors discussed experimental design for the analysis of electrical power distribution systems, which is useful to construct and empirically verify the qualitative model of a distribution system. The reliability benefits are appreciated from a customer point of view. A properly located, installed and operated DG improves the reliability of energy supply. It is essential to those places, where interruption of service is unacceptable, economy, health and safety is impacted [6]. Each customer decides his own reliability.

Fang et al. [7] introduced Sequential Monte Carlo simulation method for assessing reliability of micro-grid. Moreover for simulating the hourly wind speed of a site a Weibull distribution wind speed model is developed. Billinton et al. [8] presented the model for evaluating overall power system reliability by using a test system. Furthermore extension of the existing system is done by introducing sub-transmission and distribution lines. To enhance the advantages of battery storage system in distribution feeder, Nagarajan et al. [9] developed a generalized framework for strategic placement of battery energy system. For that purpose convex optimization problem is specifically developed. Bass et al. [10] developed a methodology to determine the capacities of BES for accommodating a PV penetration inside a distribution feeder. To investigate the role of municipal parking lot for enhancing the distribution system reliability during outages, Farzin et al. [11] incorporated vehicle-to-grid (V2G) programs. These parking lots treated as distributed storage system and are probabilistically modeled for different reliability studies. Chen et al. [12] discussed a group of methodologies such as Markov model based analytical approach and Monte Carlo simulation approach to assess and verify the reliability of mobile BESS in distribution system, respectively. Firuzabad et al. [13] investigated the impact of DG

installations on distribution system reliability. For this purpose an analytical probabilistic approach with reliability model is proposed. Yun et al. [14] proposed the different methods of evaluating distribution system reliability by considering the momentary interruptions. Falaghi et al. [15] computed the various reliability indices such as SAIFI, SAIDI and CAIDI for DG's reliability assessment. Borges et al. [16] presented a method to evaluate the effect of DG placement on voltage profile, reliability and system losses of distribution system. Adefarati et al. [17] proposed a Markov process based reliability assessment model of the distribution system that incorporated PV, BES and WTG. To measure the effects of placement of BESs, network switching and reinforcement on renewable power interaction in distribution system, Santos et al. [18] presented a novel methodology. A multi-objective stochastic model based on mixed integer linear programming is derived. To find the impact of BES, WTG, DG and PV on distribution system reliability assessment, Adefarati et al. [19] presented an analytical method. Kjolle et al. [20] proposed a specific reliability model for radially operated distribution systems. For reliability calculation analytical approach is adopted, which connected component failure rates to load point outages. Andoni et al. [21] discussed various curtailment rules generally utilized in renewable power project in United Kingdom. The impacts of these rules on the investment of renewal power production are also discussed. Moreover a novel curtailment rule is proposed for fair allocation of curtailments among different generators. Haddadian et al. [22] evaluated the synchronization between electric vehicles and renewable energy sources to alleviate imbalance of energy. Further impacts of such integrations for social and environmental sustainability are also investigated. Ghatikar et al. [23] presented a cost effective solution technique for leveraging the existing DER infrastructure and technology as well as cost optimization.

In this paper authors evaluate the reliability of Hawassa distribution feeder line 10. Further designing of Hawassa distribution feeder line is done with distributed energy sources like solar, wind and battery storage. Authors also examine the impact of grid connected distributed generation sources on existing distribution network reliability assessment for customers power delivery. Further, measures for enhancing the reliability of Hawassa distribution feeder line 10 are presented. Section 2 described the various distributed generation models. In Section 3, a case study of Hawassa distribution feeder 10 is discussed. Section 4 provided reliability analysis of the Hawassa distribution system feeder 10 in the base case environment. Section 5 presented reliability analysis with various solutions of improving the reliability of distribution

feeder 10. Section 6 provided the results and discussion followed by the conclusion.

2 Distributed Generation Model

In this work, the reliability of distribution system containing distributed energy resources such as wind and solar energy is assessed. It is well known fact that solar irradiance and wind speeds are both intermittent; hence the output powers of PV and WT systems are not deterministic. That brings up the need for a stochastic model to simulate PV and WT outputs. The stochastic model is a simulation-based technique to describe a non-deterministic behavior and the randomness of the system. The probability distribution, therefore, can be used to predict the output power of PV and WT. In order to find statistical data of the wind speed and solar insolation, meteorological data of a variety of weather conditions at one location should be measured.

2.1 Modeling of PV Power Output

The building block of PV arrays is the solar cell, which is basically a p-n junction that directly converts solar energy into electricity. It has an equivalent circuit as shown in Figure 1:

The current source I_{ph} represents the cell photo current; R_j is used to represent the non-linear impedance of the p-n junction; R_{sh} and R_s are used to represent the intrinsic series and shunt resistance of the cell, respectively. Usually, the value of R_{sh} is very large and that of R_s is very small, hence they

Figure 1 Equivalent circuit of a PV cell.

may be neglected to simplify the analysis. I_{rs} is the cell reverse saturation current, which is assumed zero. PV cells are grouped in larger units called PV modules, which are further interconnected in series-parallel configuration to form PV arrays or PV generators [24]. The PV mathematical model used to simplify our PV array is represented by the Equations (1) to (5):

(Assuming $R_s = 0$, $R_{sh} = \infty$ and $I_{rs} = 0$, for simplifying the study) and applying Kirchhoff law; The electrical powers generated by a PV array consist of modules is computed using the following equations:

$$T_C = T_A + \frac{(N_{oct} - 20)S}{80} \quad (1)$$

$$I = I_{ph} = [I_{sc} + K_i(T_c - 25)] \frac{S}{100} \quad (2)$$

$$V = V_{OC} - K_v T_c \quad (3)$$

$$FF = \frac{V_{mpp} * I_{mpp}}{V_{oc} I_{sc}} \quad (4)$$

$$P_{out} = N * FF * I = n_s * n_p * FF * V * I \quad (5)$$

Where, I is the PV array output current, V is the PV array output voltage, n_s, n_p is the number of cells in series and in parallel, N is number of module, T_C, T_A are the cell effective and ambient temperatures in °C, respectively, I_{sc} is the cell short-circuit current, V_{oc} is the open circuit voltage, I_{mpp}, V_{mpp} are the current and voltage at maximum power point, respectively, K_i is the short circuit current temperature coefficient, K_v is the open circuit voltage temperature coefficient, S is the solar radiation in mW/cm^2 and FF is the fill factor.

2.2 Modeling of WT Power Output

The output power of a wind turbine depends on wind velocity. If the wind velocity is below the cut-in speed, there is insufficient wind energy to generate power, and the wind turbine would be turned off. If the wind velocity is between the cut-in and rated speed, the output power would be variable. If the wind velocity is between the rated and cut-on speed, the output power would be constant. In case, if wind speed goes above cut-on speed, the wind turbine would be turned off because it exceeds the mechanical safety limit. The relationship between the output power and wind velocity is shown in Figure 2, and to model the wind system performance, its power curve must be formulated in the form of polynomials as given below [25]. The output of wind turbine generator is provided by the Equation (6).

Figure 2 Output characteristics curve of wind turbine.

$$P_{WTG} = \begin{cases} 0 & 0 \leq V_t \leq V_{ci} \\ A + BV_t^3 & V_{ci} \leq V_t \leq V_r \\ P_r & V_r < V_t \leq V_{co} \\ 0 & V_t > V_{co} \end{cases} \quad (6)$$

Where, P_{WTG} and V_t represent the output of wind turbine and actual wind velocity, respectively, at time t ; V_{ci} , V_r and V_{co} represent the cut-in wind velocity, rated wind velocity and cut-off wind velocity, respectively; P_r represents the rated power of the wind turbine. and are the parameters, which can be calculated by the Equations (7) and (8):

$$A = \frac{P_r * V_{ci}^3}{V_{co}^3 - V_r^3} \quad (7)$$

$$B = \frac{P_r}{V_r^3 - V_{co}^3} \quad (8)$$

Although wind is random and intermittent, distribution of wind velocity in most districts still follows some rules and certain distributions is adopted to represent the probability distribution of wind velocity. Consequently, a probabilistic method should be implemented to simulate the uncertainty of the wind speed. Statistical data has shown that probability distribution of wind speed follows the Weibull distribution. It is considered to be a simple function

suitable to describe the wind [26]; it's a single-peak and two-parameter function, whose distribution and probability density functions are expressed by Weibull distribution as shown in Equation (9) [19]:

$$f(V_t) = \frac{k}{c} \left(\frac{V_t}{c} \right)^{k-1} \exp \left[- \left(\frac{V_t}{c} \right)^k \right] \quad (9)$$

Where, V_t represents wind speed, C is Scale parameter, and K represents Shape parameter. Both parameters are calculated from the average wind velocity (μ) and the standard deviation (σ), as shown in Equations (10) and (11).

$$k = \left(\frac{\sigma}{\mu} \right)^{-1.086} \quad (10)$$

$$c = \frac{\mu}{\Gamma\left(1 + \frac{1}{k}\right)} \quad (11)$$

Since the Weibull probability function of the wind speed is very much sensitive to any change in c and k , statistical data of the wind speed at the desired location should be collected for several years.

2.3 Battery Storage System Model

Storage device is usually configured with intermittent generations like wind power and photovoltaic in order to minimize the fluctuation of these DGs' output, to improve the power quality and power supply reliability in micro grid. In islanded mode, when DGs' output is greater than load, residual energy is stored in storage device; when DGs' output is less than load, the stored energy is released to supply customers. Assume that the combined DGs and storage energy system is autonomous and controllable; neglecting the influence of the time constant of power regulation. It is considered that output of the combined DGs and battery energy storage system is in equilibrium with load, all the time. DGs' output is insufficient when the wind or sunlight is not/less available. At that time the released energy by storage device is greater than the stored energy and then the operation time of storage system is constrained by its storage capacity. In addition, battery storage is associated with the distributed energy resources to supply the load when the main source is not available. In this work, a generic battery storage system is developed, which serves the main purpose of this study.

The total system energy interrupted capacity and the converter capacity are 2400 kWh and 400 kW, respectively for 24 hours. Figure 3 shows the

Figure 3 400 kW PV hourly charge and discharge profile of the storage ($P > 0$ charging and $P < 0$ discharging).

hourly charge and discharge profile of the battery storage. Because there is no output power of the PV during the night, the battery storage is charged by the main grid. During interruptions in the power network, the load is drawn up to 2400 kWh energy for 6 hours, if the battery is fully charged. Batteries used in all solar systems are sized in 0 Ampere hours, under the standard test conditions (Temp: 25°C). Equation (12) represents the capacity of battery bank for a specified discharge rate, in ampere hours.

$$C_x = \frac{E_{tot}}{V_{dc}} * \frac{G_{ft}}{DOD_{max}} \quad (12)$$

Where, C_x represents the battery capacity, for a specified discharge rate in ampere hours, provide the total energy in watt hours, E_{tot} which to be supplied by battery bank during grid failure, G_{ft} is the number of days that battery bank needs to supply during grid failure DOD_{max} and represents the design for maximum depth of discharge.

3 Case Study

3.1 Meteorological Data

Table 1 presents the calculated and measured values of basic parameters for Hawassa city.

Table 2 presents the wind speed at different height.

Table 1 Calculated and measured values of basic parameters for Hawassa city

Month	H _o Average	Declination Angle (°)	Sunset Hour Angle (ωS)	Monthly Average Daily Maximum Bright Sunshine (S)	Average Monthly Day Length (S _o)	Estimated Monthly Average Irradiation (H _{est})	Measured Monthly Average Irradiation, H _{meas.} (NASA)
Jan.	9.87	-17.78	87.73	10.15	11.698	6.59	6.02
Feb.	9.72	-8.67	88.92	9.76	11.856	6.33	6.41
Mar.	9.52	3.62	90.45	9.11	12.0596	5.93	6.35
Apr.	9.26	14.59	91.84	8.05	12.2452	5.36	6.04
May.	8.96	21.90	92.84	6.63	12.379	4.64	5.95
June.	8.94	23.19	93.03	6.22	12.404	4.45	5.42
July.	8.99	18.17	93.03	6.58	12.404	4.62	4.83
Aug.	8.92	8.11	91	7.18	12.13	4.98	5.01
Sep.	9.12	-3.82	89.53	7.11	11.94	5.00	5.64
Oct.	9.16	-15.06	88.09	7.29	11.747	5.15	6.04
Nov.	9.48	-21.97	87.15	8.65	11.6198	5.87	6.25
Dec.	9.48	-23.09	86.99	8.65	11.5983	5.88	6.10
Aver.				7.95		5.4	5.84

Figure 4 Monthly average global irradiation of Hawassa city.**Table 2** Wind speed at different height

Monthly averaged wind speed at 50,100,150 and 300m above the surface of the Earth(m/s) Vegetation type "Airport"; flat rough grass														
Lat. 7.03 Lon.38.29	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual Average	
50m	4.49	4.05	3.84	3.93	3.72	3.67	3.19	2.96	3.05	3.66	4.20	4.47	3.76	
100m	4.98	4.50	4.26	4.36	4.12	4.07	3.53	3.28	3.38	4.06	4.66	4.95	4.18	
150m	5.29	4.78	4.52	4.63	4.38	4.32	3.76	3.49	3.59	4.31	4.95	5.27	4.44	
300m	5.87	5.31	5.02	5.14	4.86	4.80	4.17	3.87	3.99	4.78	5.49	5.84	4.93

Figure 5 System configuration with charge controller and the inverter.

3.2 Component Selection

All solar systems are designed to solve a particular power problem; the grid connected system with a battery backup has two main functions:

- To supply power to all the loads when the grid has failed for a specified period
- To supply AC power to the national grid when there is excess power

The selected configuration for grid connected PV systems with battery backup has the charge controller and the inverter as a unit; Figure 5 shows the block diagram of a system.

Block diagram shows a design configuration for supply and storage system. When the demand is high, the system will deliver energy from inverter current. But when the demand is low, the battery will store energy by solar panel through charge controller. The stored energy is used as backup for gloomy day or at night [27].

3.3 Module Selection

PV module selection criteria are as follows:

- The performance warranty in case of any problems
- Module replacement ease
- Compliance with natural electrical and building codes
- Manual should be available to see the quality and characteristics of module Table 3 describes the typical electric characteristics of generic poly 250 W module.

Table 3: Typical Electric Characteristics of Generic poly 250 W Module

Table 3 Typical electric characteristics of generic poly 250 W module

Type	Polycrystalline
Power (max)	250 W
Voltage @ Max. power point	30 V
Current @ MPP	8.33 A
V_{oc} (open circuit voltage)	36.4 V
I_{sc} (Short circuit current)	8.63 A
Conversion Efficiency(per module area)	17 %
Area (dimension)	1.627 m ²
Nominal voltage	24 V
Max. system voltage	600V DC
Max. series fuse rating	750V DC
Temperature derating factor	0.06%/°C

3.4 Inverter Selection

Table 4 presents the electrical characteristics of IG PLUS 150 V-3 inverter.

Table 4 Electrical characteristics of IG PLUS 150 V-3 inverter

Continuous output power	400 kW
Weighted efficiency(CEC)	95.5 %
Maximum DC input voltage	800 V
DC peak power tracking range ($V_{mpp\ min} - V_{mpp\ max}$)	500–750 V
DC max. current (A)	700A
AC nominal voltage (V)	400 V
AC frequency (Hz)	50 Hz

Based on the data available, the characteristics of PV, WT and battery storage system are calculated in Tables 5, 6, 7, respectively.

Table 5 Calculated PV generator characteristics

S.no	Name of RDG	P_{rated} [kW]	Number of Module	Inverter $V_{mpp\ max}$	Array Mpp DC Voltage	Array mpp DC Current	Number of Module in Series	Number of Module in Parallel	Actual Power Output P_{out} , [kW]
1	PV	400	1600	600	600	492	20	80	228.5

Table 6 Calculated storage battery basic parameters data

S.no	Model of Battery	Total Number of Cells Connected	Total Energy Supplied to the Grid	Battery Capacity
1	JC DYNASTY	300	400*6 kWh = 2400 kWh	1428.6Ah

Table 7 Calculated wind turbine generator wind characteristics data

S.no	Name of RDG	P _{rated} [kW]	Average Wind speed at				Output Power
			100 m	V _{ci} [m/s]	V _r [m/s]	V _{co} [m/s]	
1	WGT1	100	4.18	2 m/s	11m/s	50m/s	65.53

4 Reliability Analysis of the Hawassa Distribution System Feeder 10

4.1 Existing Structure of Hawassa Distribution System Feeder 10

The area chosen for the current study is Hawassa substation distribution system feeder 10 line. The power distribution has only one substation, with 132kV/33kV primary distribution voltage level (medium voltage), as shown in Figure 6.

4.2 Data Collected from Hawassa Substation 33 kV Feeder Line

Hawassa town has only one substation, 13 outgoing feeders out of which 3 are 33 kV, around 50 MW peak load, and approximately 29,906 customers (i.e. industrial, commercial and residential). The collected data for 33 kV feeder line of Hawassa Substation are shown in Table 8. The frequency of

Figure 6 Single line diagram of existing structure of Hawassa substation 33 kV feeder 10 line.

interruption and duration of interruption for Hawassa 33kV distribution system for 11 months are analyzed and interpreted as shown in Figures 7 and 8, respectively. The collected data is recorded for eleven months.

Table 8 Hawassa substation of 33 kV lines data

Substation Name/Feeder Name	33kV Power Transformer Capacity	Line MV(33kV)	Transformer Qty.(kVA)	Location/Name
Hawassa/F9		2	2*1250	Hawassa BGI
Hawassa/F10	16/8/8MVA	120.7	1*25,8*50,6*100, 1*200,1*500	Arbegona,kokosa,boro, Hududa,Bokore so on
Hawassa/F11		7	5*630,1*500	Hawassa university

Figure 7 Frequency of Interruption for Hawassa sub-station 33kV feeder line 10.

Figure 8 Duration of interruption for Hawassa sub-station 33kV feeder line 10.

Table 9 Summarizing the interruption data on 33kV feeder line 10

No.	Type of the Fault	Frequency	Duration	Percentage of Fault (%)
1	Distribution fault (open, short, earth)	269	515.05	80.30
2	Line and transformer Overload fault	14	53.14	4.18
3	Generation failure or system overload (Shading)	52	104.01	15.52

From the analysis, it is observed that majority (80.30%) of the faults in Hawassa substation feeder 10 distribution network are due to short circuit, open circuit and earth faults. The remaining faults are due to black out, operation and system over load (when generated power is below the total demand other than black out), as shown in Table 9.

4.3 Reliability Evaluation of Hawassa 33kV (feeder 10) Distribution System

One objective of this work is to provide a more acceptable method for determining distribution network reliability. This part of the work uses IEEE 1366 indices to evaluate the reliability indices of Hawassa 33 kV feeder 10. The availability of power for customers from this substation is calculated on the medium voltage side of customer transformers (33kV). The customer-oriented indices (SAIFI, SAIDI, CAIDI, ASAI, ASUI) for Hawassa substation feeder 10 is calculated using ETAP (Electrical Transient Analyzer Program) software [28].

4.4 Algorithm for Reliability Indices Evaluation Using ETAP

4.4.1 Single line diagram

The starting point of any power-flow problem is the development of a single-line diagram of the power system, from which computer solutions is obtained. The single line diagram of the 33kV Hawassa substation feeder line 10 is drawn using the ETAP Power Station platform for this study. All the organized data is fed to a single-line diagram. Partial view of the single-line diagram is given in Figure 9, for both editing and running modes of ETAP.

Figure 9 Single line diagram of Hawassa substation 33kV feeder 10 distribution system.

4.4.2 Inputs data based on the type of fault

4.4.2.1 Distribution line fault (open circuit, short circuit, earth fault)

Table 10 presents the reliability indices related to distribution line fault interruption.

4.4.2.2 Distribution line and power transformer overload

Table 11 provides the overload interruption reliability indices for distribution line and power transformer.

4.4.2.3 Generation failure or system overload (shading)

Table 12 provides the load point interruption reliability indices for generation failure and system overload.

The failure rates and repair duration of different components such as power transformers, feeder, breakers, and bus bars are presented in Table 13. 132/33 kV transformers are considered with the rating of 16MVA.

4.5 Base Case Reliability Analysis

The base case test system used for the reliability analysis is discussed in this section and shown in Figure 9. The ETAP generated individual load point

Table 10 Distribution line fault interruption reliability indices

No.	Location Name/ Node Points/	Distance from Source Point	Frequency	Annual Outage Duration (hr/yr) U_s	Average Outage Rate (f/yr/km) f_s	Average Outage Duration (hr/yr/km)	Mean Time to Repair (hr) r_s
1	A/Hogiso 1,2/	46 km	269	515.05	0.85	11.2	1.91
2	B/Hududa/	51 km	269	515.05	0.94	10.1	1.91
3	C/Homba/	58 km	269	515.05	1.07	8.88	1.91
4	D/Boro/	63 km	269	515.05	1.16	8.18	1.91
5	E/Arbegona 1, 2/	74 km	269	515.05	1.37	6.96	1.91
6	F/Arbegona 3,4,5,6/	76.5 km	269	515.05	1.41	6.73	1.91
7	G/Kokosa 1, Kokosa tele, Kokosa hospi. /	82 km	269	515.05	1.51	6.28	1.91
8	H/Kokosa 2/	82.7 km	269	515.05	1.53	6.23	1.91
9	I/ Gerba hurufa/	96.7	269	515.05	1.79	5.33	1.91
10	H/Bokore/	120.7	269	515.05	2.23	4.27	1.91

Table 11 Distribution line and power transformer overload interruption reliability indices

No.	Location Name/ Node Points/	Distance from Source Point	Frequency	Annual Outage Duration (hr/yr) U_s	Average Outage Rate (f/yr/km) f_s	Average Outage Duration (hr/yr/km)	Mean Time to Repair (hr) r_s
1	A/Hogiso 1,2/	46km	14	53.14	0.044	1.16	3.8
2	B/Hududa/	51km	14	53.14	0.049	1.04	3.8
3	C/Homba/	58km	14	53.14	0.056	0.92	3.8
4	D/Boro/	63km	14	53.14	0.06	0.84	3.8
5	E/Arbegona 1, 2/	74km	14	53.14	0.071	0.72	3.8
6	F/Arbegona 3,4,5,6/	76.5km	14	53.14	0.073	0.69	3.8
7	G/Kokosa 1, Kokosa tele, Kokosa hospi. /	82km	14	53.14	0.078	0.65	3.8
8	H/Kokosa 2/	82.7km	14	53.14	0.08	0.64	3.8
9	I/ Gerba hurufa/	96.7	14	53.14	0.09	0.55	3.8
10	H/Bokore/	120.7	14	53.14	0.12	0.44	3.8

Table 12 Generation failure and system overload load point interruption reliability indices

No.	Location Name/ Node Points/	Distance from Source Point	Frequency	Annual Outage Duration (hr/yr) U_s	Average Outage Rate (f/yr/km) f_s	Average Outage Duration (hr/yr/km)	Mean Time to Repair (hr) r_s
1	A/Hogiso 1,2/	46km	52	104.01	0.15	2.26	2.0
2	B/Hududa/	51km	52	104.01	0.17	2.04	2.0
3	C/Homba/	58km	52	104.01	0.19	1.79	2.0
4	D/Boro/	63km	52	104.01	0.21	1.65	2.0
5	E/Arbego 1, 2/	74km	52	104.01	0.25	1.41	2.0
6	F/Arbego 3,4,5,6/	76.5km	52	104.01	0.26	1.36	2.0
7	G/Kokosa 1, Kokosa tele, Kokosa hospi. /	82km	52	104.01	0.28	1.27	2.0
8	H/Kokosa 2/	82.7km	52	104.01	0.29	1.26	2.0
9	I/ Gerba hurufa/	96.7km	52	104.01	0.34	1.08	2.0
10	J/Bokore/	120.7km	52	104.01	0.43	0.86	2.0

Table 13 Component reliability data

Component Type	Average Outage Rate (f/yr/km), f_s	Mean Time to Repair (hr), r_s	Switching Time (hr)
Power transformer	0.075	10	1
Circuit breaker	0.04	4	1
Main bus bars	0.02	4	1
Utility grid	0.02	24	1
Feeder	0.3	6	1

system reliability indices report are shown in Figure 10. As a radial system, with no meshed connections, the average outage rate (λ) increases as the load point are farther from the supply point; however, the average duration time tends to be smaller. The mean time to repair (r_s) and annual outage duration are assumed to be constant value.

Different system reliability indices calculated for 33kV feeder line 10 are shown in Table 14.

4.6 Comparison of Reliability Indices with Benchmarks

Reliability benchmarks are the standards against which analyzed or measured reliability is judged. The purposes of reliability benchmarks are to

Load Point Output Report

			Average Interrupting Rate	Average Outage Duration	Annual Outage Duration	EENS
ID	Bus Load Sector	Connected Bus ID	f / yr	hour	hr / yr	MW hr / yr
L1	Residential	LB1	47.5205	1.80	85.3316	4.2324
L2	Residential	LB2	47.5205	1.80	85.3316	2.5386
L3	Residential	LB3	47.5205	1.80	85.3316	1.8773
L4	Residential	LB4	47.5205	1.80	85.3316	2.0480
L5	Residential	LB5	47.5205	1.80	85.3316	4.9492
L6	Residential	LB6	47.5205	1.80	85.3316	10.5679
L7	Residential	LB7	47.5205	1.80	85.3316	3.6266
L8	Commercial	LB8	47.5205	1.80	85.3316	3.6266
L9	Commercial	LB9	47.5205	1.80	85.3316	5.8025
L10	Industrial	LB10	47.5205	1.80	85.3316	10.8798
L11	Residential	LB11	47.5205	1.80	85.3316	6.8905
L12	Govt. & Inst.	LB12	47.5205	1.80	85.3316	1.3781
L13	Residential	LB13	47.5205	1.80	85.3316	5.7599
L14	Govt. & Inst.	LB14	47.5205	1.80	85.3316	20.4965
L15	Commercial	LB15	47.5205	1.80	85.3316	3.3365
L16	Residential	LB16	47.5205	1.80	85.3316	3.6266
L17	Residential	LB17	47.5205	2.05	97.3716	2.0691
						93.7062

Figure 10 Load point output report for base case Hawassa substation feeder line 10.**Table 14** System indices of 33kV feeder line 10

System Indices	
SAIFI System Average Interruption Frequency Index	47.5205 f/cust.yr
SAIDI System Average Interruption Duration Index	85.4837 hr/cust.yr
CAIDI Customer Average Interruption Duration Index	1.799 hr/cust.inter
ASAI Average Service Availability Index	0.9902
ASUI Average Service Unavailability Index	0.00976
EENS Expected Energy Not Supplied	93.706 MW hr/yr

define minimum average reliability performance, by feeder type, for a distribution network. It provides a basis against which a distribution network service provider's reliability performance is assessed. The benchmarks were calculated using the IEEE Guide for electric power distribution reliability indices – IEEE Standard 1366–2003. A benchmark of SAIDI, CAIDI, SAIFI and ASAI for nine countries is shown in Table 15. From the calculation

Table 15 Benchmarks for Reliability Indices [27]

No	Country	SAIDI (Minutes/ year)	SAIFI (Interruptions/ Customer)	CAIDI (Minutes/ outage)	ASAI (%)
1	United States	240	1.5	123	99.91
2	Austria	72	0.9	112	99.97
3	Denmark	24	0.5	70	99.981
4	France	62	1	58	99.97
5	Germany	23	0.5	50	99.9999
6	Italy	58	2.2	106	99.9991
7	Netherlands	33	0.3	75	99.97
8	Spain	104	2.2	114	99.968
9	UK	90	0.8	100	99.964

and analysis considered in reliability evaluation of Hawassa substation 33kV feeder line 10, distribution system has an average value of SAIDI, SAIFI, CAIDI, ASAI and ASUI are 85.4837 hr/customer (5105 min.), 47.5205 interruptions/customer, 1.799 hr/customer (107.4 minutes), 99.02% and 0.976%, respectively. A higher SAIDI, SAIFI and CAIDI index number indicates worse performance. Lower number for SAIDI, SAIFI and CAIDI index indicates better reliability performance; i.e., a lower frequency of outages or shorter outage duration. Comparing the average value of SAIDI, SAIFI, CAIDI and ASAI for feeder line 10 of Hawassa distribution with the benchmark shows that it has the worst performance.

4.7 Loss of Revenue Due to Power Interruption

A common approach used in quantifying the worth or benefit of electric-service reliability is to estimate the customer costs associated with power interruptions. The customer interruption cost, when an electric supply failure occurs, depends on many factors. The absence of sufficient data sets, required in a detailed evaluation of the customer outage costs, makes it difficult to estimate precise individual customer outage costs due to a specific failure event. This part of work estimates only the loss of cost by the utility due to interruptions in Hawassa feeder 10. Table 16 presents the electricity tariff of Ethiopian Electric Power Corporation (EEU) since July 8, 2006 [27].

The cost of energy, which is not supplied due to interruption for Hawassa Substation, is calculated by multiplying power with time and tariff of electricity. By considering an average price of 0.6Birr/kWh for electricity in EEU,

Table 16 Electricity tariff of Ethiopian electric power corporation

Tariff Category	Block Identification	Monthly consumption (kWh)	Birr (kWh)
Domestic	1st Block	0–50	0.273
	2nd Block	51–100	0.3564
	3rd Block	101–200	0.4993
	4th Block	201–300	0.55
	5th Block	301–400	0.5666
	6th Block	401–500	0.588
	7th Block	Above 500	0.6943
General	1st Block	0–50	0.6088
	2nd Block	Above 50	0.6943
Low Voltage Time of Day Industry	Peak	–	0.5085
	Off – Peak	–	0.3933

the average energy and cost of energy not supplied due to power interruption for Hawassa substation feeder 10 in 2015 is shown in Table 14, which is 93.706MWh/yr. Therefore, the cost of energy is $(0.6 * 1000 * 93.706)$ (56223 birr or 2530.062\$).

5 Solutions for Improving the Reliability of Distribution Feeder

The work concentrates to conduct a study on design and distributed generation of Hawassa 33kV feeder line 10. The proposed types of solution for improving the reliability of distribution system are as follows:

1. **Design Solution:** By enhancing the existing capacity of distribution cables and transformers
2. **Security Strategy Solution:** By improving operation, maintenance and automation
3. **Adequacy Solution:** By incorporating distributed renewable energy generation

From the Figure 11, the pink color at branch point A reflects that the voltage drop is acceptable; but at points B and J, the red color shows that the voltage-drop is in unacceptable range. This figure also reflects that the transformers at points A, E and G are overloaded.

The study encompasses lines and transformers of existing voltage level of 33kV and extend to high voltage substation lines and transformer. After completing the one line diagram with the necessary data, load flow simulation

Figure 11 Running case of Hawassa 33kV feeder 10.

was executed. The load flow simulation report also delivers the voltage profiles of each branching points in the network. Poor voltage profile (under voltage) of branching points shows that except the first branching node point all other are under voltage (red colored) and total voltage drop of the distribution line violates $\pm 5\%$ of nominal voltage value for 33KV line, hence that needs re-conductoring with better cable capacity. The distribution transformers at node point A, E and G are overloaded (red colored) so that needs upgrading.

5.1 Design Solution

For the design of power distribution system all materials and workmanship should be of the best standard and comply with the relevant legislation and Ethiopian Standards, or if such do not exist, with the relevant IEC or International Standard Organization (ISO) Standards [29]. The recommendations for the design are as follows:

- The Hawassa substation distribution system is mainly radial network, which is making things worse in case of line tripping. So it is better to convert radial networks to ring network for better reliability. There is severe under voltage drop branch point B up to G.

- Distribution transformers are without surge arrestors and drop out fuses at the majority of locations. So, it will be better that the distribution transformers with their accessories are equipped with surge arresters and drop out fuse.
- Various kVA ratings for distribution ranging from 50, 100, 200, 315, 500 etc. exists in Hawassa feeder 10 distribution line. Ratings of distribution transformers need to be standardized to avoid spare inventory and overloaded. For better distribution reliability, loads or customers should be separated by specifying industrial, commercial and residential consumers.

5.1.1 Selection of distribution transformer capacity

Electric power utilities frequently face a common challenge of efficiently determining the transformer size to provide service for their customers. Inaccurate estimation of transformer size ultimately leads to problems related to reliability issues and excessive costs [30]. Supply a transformer much larger than necessary to a customer, results in excessive capital costs and future costs of transformer losses resulting from large no-load losses. On the other hand, under sizing a transformer for a particular application leads to reliability problems and reduced transformer service life. Therefore, proper selection of transformer size is important from financial saving and energy loss reduction perspectives. There are varying practices around the world towards selecting the size and number of distribution transformers; each one trying to match the desired operational conditions with the technical characteristics of the system. In some countries, distribution transformers are installed very close to the loads that they are supposed to serve. So in our case distribution transformers at node point A, E and G have to be upgraded as expressed below.

- At node point A since the load is 58.4kVA the capacity of the transformer should be upgraded to 100kVA
- At node point E since the load is 146kVA the capacity of the transformer should be upgraded to 200kVA
- At node point G since the load is 79.4kVA the capacity of the transformer should be upgraded to 100kVA

5.1.2 Selection of distribution cable

In order to select an appropriate cable size for the secondary side of power transformers, it is necessary to know the following points:

Table 17 AAC overhead cables data

Nominal Area (mm ²)	Approximate Over All Diameter Mm	Approximate Weight Kg/km	Nominal Resistance Ohm/km	Nominal Reactance Ohm/km	Current Rating A
35	6.9	1780	1.11	0.164	120.6
50	8.1	1970	0.822	0.156	157.3
70	9.7	2260	0.568	0.145	178.3
95	11.4	2600	0.411	0.137	204.5
120	12.8	2880	0.325	0.136	262.2
150	14.2	3280	0.265	0.131	319.9
185	15.7	3640	0.211	0.127	361.8

Note: The values of current rating mentioned in above Table are based on wind velocity of 0.6 meter/second, solar heat radiation of 1200 watt/metre², ambient temperature of 50°C & conductor temperature of 80°C.

For secondary (33 kV) Side, 33 kV Feeder's maximum rating is 8MVA. So, the rated current is calculated by Equation (13)

$$I_{rated} = \frac{MVA}{\sqrt{3} * V} \quad (13)$$

The calculated value of secondary rated current is 139.96 A.

By considering a De-rating factor of 0.85, the standard current that flows through the primary cable is given by Equation (14)

$$I_{standard} = \frac{I_{rated}}{Derating\ factor} \quad (14)$$

The calculated value of standard current is 164.66 A.

From the Table 17, the data shows that a 3*95 mm² AAC Overhead cables would be capable of carrying a load current of 204.5A.

5.1.3 Permissible voltage drop calculation and power loss calculation

Permissible voltage drop is computed by calculating the highest current drawn by the load multiplied by an appropriate factor. The maximum voltage drop allowed by SANS 10142-1 during full load running condition is 5% [31]. The voltage drop can be calculated by two different ways:

- Multiplying the current by the impedance of the length of the cable. Calculate the percentage voltage drop by reference to the phase to earth voltage

- Multiply the current by the length of cable, and then multiply the result by the voltage drop per amp per meter

Here in this work, the voltage drop is calculated by using Equation (15).

$$V_{3\varphi drop} = \sqrt{3} * \left(\frac{R_{\cos\varphi + \sin\varphi}}{km} \right) * I_{load\ current} * D \quad (15)$$

Where, D is distance in km.

From Table 17, for 50 mm², the impedance per kilometer is 0.84343 Ω/km and the average distance from Hawassa substation to study area is 91.7 Ω/km.

The voltage drop in the secondary feeder is calculated by calculating power losses. Power losses (variable) or copper losses in distribution lines (feeders) can be calculated by taking longest distance of the feeder line equal to 120.7 km. Therefore, real power loss is calculated by using Equation (16).

$$P_{loss} = \sum_{i=1}^n I_i^2 * R_i \quad (16)$$

The calculated value of active power losses is 60.04 kW.

Similarly, the reactive power loss is calculated by using Equation (17).

$$Q_{loss} = \sum_{i=1}^n I_i^2 * X_i \quad (17)$$

The calculated value of reactive power losses is 11.39 kVAr.

5.1.4 Re-conductoring of feeder line by higher capacity conductor

From the Table 17, the data shows that 3*95 mm² AAC Overhead cables would be capable of carrying a load of 325.9A. The voltage drop for the above case is calculated by Equation (18). Here, $I_{load\ current}$ is 23.2 A and Z 0.411 + j 0.137Ω/km.

$$V_{drop} = \sqrt{3} * \left(\frac{0.411 * 0.85 + 0.137 * 0.53}{km} \right) * 24.6 * 917 \quad (18)$$

The calculated value of voltage drop is 1648.7V. The percentage voltage drop value is 4.99%. This value of voltage drop is acceptable. Further, the Power losses are calculated by taking the longest distance equal to 120.7 km. In the above case the value of real and reactive power losses are 30.02 kW and 10 kVAr, respectively. The above loss calculation only covers losses in cable line; it doesn't cover no-load and full load loss of distribution transformer.

5.1.5 Fault current calculation

Electric cables are designed to operate below a certain maximum temperature, this being dependent on the conductor material and the type and the thickness of the insulation. Cable selection for a particular installation must therefore be made within the affordable temperature limits. For a power transformer with the rating of 132/33 kV, 32 MVA, the short-circuit capacity is 800 MVA (IEC 60076–5). The earth fault level is 100 MVA, and it may be assumed that the fault should be cleared within a half second. For secondary 33 kV side, the short circuit and earth fault current calculations are as follows:

5.1.5.1 Short circuit current calculation

The supply impedance seen from the primary side is 21.78Ω . The calculated value of supply impedance transferred to the secondary side is 1.36Ω . The value of short circuit current on the secondary side is 14.009 kA. The short circuit current withstand capacity of the cable is calculated by Equation (19).

$$I_{sc} = \frac{K_s * A}{\sqrt{t}} \quad (19)$$

Where, I_{sc} is the Short circuit current rating of cable in kA, A represents the cross-section area of conductor in mm^2 , which is 50 mm^2 in this calculation, t is the time require for tripping in seconds, here its value is 0.5 seconds and K_s represents the constant that depends on the conductor material and temperature. In this work, K is selected 105 A/mm^2 for XLPE, Aluminum conductor. The calculated value I_{SC} of is 7.42 kA. Therefore, the cable cannot withstand the prospective short circuit current, if the cable is aluminum conductor with the area of 50 mm^2 .

By taking cable size of 95 mm^2 XLPE, Aluminum conductor the short circuit capacity will be 14.106 kA. Therefore, the cable can withstand the prospective short circuit current.

5.1.5.2 Earth fault current calculation

The cable earth fault current that can exist in the secondary feeder is calculated by Equation (20). The calculated value of I_{EF} is 1.75 kA.

$$I_{EF} = \frac{\text{Earth Fault MVA}}{\sqrt{3} * \text{Voltage Rating}} \quad (20)$$

The cable earth fault current withstand capacity is calculated by Equation (21)

$$I_{EF} = \frac{K_e * A}{\sqrt{t}} \quad (21)$$

Where, I_{EF} is Earth fault current in kA. A represents the cross-section area of conductor in mm^2 , which is 50 mm^2 in this calculation, t is the time require for tripping in seconds, here its value is 0.5 seconds and K_e is a constant that depends on earth path material. Here the value of K_e is 76 A/mm^2 . After substituting all the values in Equation (18), the computed value of K_e is 5.37 kA. Therefore, the cable can withstand the prospective earth fault current. In many cases, the cable conductor size is smaller than dictated by the full load current, and is not chosen in order to withstand the prospective short-circuit current. The use of large conductor should be avoided by improving the speed of protection and in the case of earth fault current, by the use of sensitive earth fault protection.

5.2 Security Strategy Solution

Due to increase in the dependence on electricity and the growth of sensitive loads in all customer sectors (residential, commercial and industrial), the utilities must strive to maximize reliability to ensure that the customer requirements are satisfied while incurring the lowest possible cost. By knowing the root causes of faults, it is possible to take actions that will prevent faults from occurring.

5.2.1 Reduction of the number of faults

The reduction of interruption frequency is feasible by decreasing failure rates of the network component. For example, the reduction of the number of faults in an overhead line can be achieved by a tree trimming program, which ensures the clearance distance. This will reduce the failure rate, and increase the system reliability as well as reduce interruption. A reduction of the number of interruptions leads to lower interruption indices. In summary, the reduction of the number of faults causes a decrease of the frequency of interruptions and unavailability. In the following list, one can find the most important measures for reducing failure rates.

- Preventive maintenance
- Monitoring critical components
- Preventive replacement of components which have reached the end of their useful life
- Isolated or tree wires in overhead lines to prevent tree contact with the conductor
- Tree trimming and periodical trimming of the adjacent vegetation to prevent contact with the conductors
- Protection against animals contact with conductors

5.2.2 Reduction of time of interruption

The time of interruption is the time required to restore the power supply. A fault affected zone in the distribution network can be isolated from the healthy part of the network by disconnecting the affected sector. It is important that the switching actions of the restoring process are optimized in order to isolate the smallest possible section of network affected by the fault. This process does not reduce the time interruption in the fault affected zone, but it will provide a substantial improvement in the sector of the network that is not affected by the fault. Furthermore, automated sectioning points will provide a more timely restoration of the power supply. If the restoration of the supply takes place in less than three minutes, the interruption is not considered as long interruption. Time reduction of the events lead to the reduction in the unavailability indices, but do not show effects on interruption frequency. ETAP shows how the indices are changed based on network atomization. The following list shows some of the most important measures for reducing the time of interruption:

- Distribution network automation
- System reconfiguration after the fault
- Fault current detection in order to localize the fault in the network
- Faster crew response due to the implementation of an outage management system, travel time coordination and an increased number of crews and dispatch centers

Analyzing the reliability of Hawassa 33kV feeder line 10 by automated system using dropout fuse and isolators in distribution network is shown in Figure 12.

From the Figure 12 it is clear that the pink color shows the voltage drop at branch point A-J and it is in an acceptable range. Also the transformers at A, E and G shows pink color because it is upgraded and not overloaded. Figure 13 presents the report generated by ETAP of Load point output for automated Hawassa substation feeder line 10.

By comparing bench mark values it is found that the values of calculated indices presented in table 18, is still not up to the satisfactory levels, but are improved by 46.13%, 53.32% and 45.35% for SAIDI, SAIFI and EENS, respectively from the base case.

5.2.3 Loss of revenue due to power interruption

The loss of revenue cost calculated in this case is 1382.724\$, which is less than pervious base case i.e. 2530.062\$.

Figure 12 Single line diagram of modified Hawassa substation feeder line 10.

Load Point Output Report

LOAD BUS			Average Interrupting Rate	Average Outage Duration	Annual Outage Duration	EENS
ID	Load Sector	Connected Bus ID	f / yr	hour	hr / yr	MW hr / yr
L1	Reside	LB1	16.1995	2.14	34.73	1.7225
L2	Reside	LB2	16.1995	2.14	34.73	1.0332
L3	Reside	LB3	16.2595	2.14	34.85	0.7667
L4	Reside	LB4	16.3195	2.14	34.97	0.8392
L5	Reside	LB5	16.3795	2.14	35.09	2.0351
L6	Reside	LB6	17.7795	2.13	37.89	4.6922
L7	Reside	LB7	17.7795	2.13	37.89	1.6102
L8	Com	LB9	19.5025	2.12	41.42	1.7603
L9	Com	LB8	19.50451	2.13	41.48	2.8205
L10	Indust	LB10	19.5025	2.12	41.42	5.2808
L11	Reside	LB11	19.5025	2.12	41.42	3.3445
L12	Govt.	LB12	27.11251	2.09	56.55	0.9133
L13	Reside	LB13	27.11251	2.09	56.55	3.8174
L14	Govt.	LB14	27.11451	2.09	56.56	13.6050
L15	Com	LB15	27.14251	2.09	56.61	2.2136
L16	Reside	LB16	39.4955	1.80	71.00	3.0175
L17	Reside	LB17	39.7655	2.06	81.86	1.7395
			51.21			

Figure 13 Load point output report for automated Hawassa substation feeder line 10.

Table 18 System indices of automated 33kV feeder line 10

System Indices	
SAIFI System Average Interruption Frequency Index	22.1833 f/customer. yr
SAIDI System Average Interruption Duration Index	46.0464hr/customer. yr
CAIDI Customer Average Interruption Duration Index	2.076hr/customer interruption
ASAI Average Service Availability Index	0.9947
ASUI Average Service Unavailability Index	0.00526
EENS Expected Energy Not Supplied	51.212 MWhr/yr
AENS Average Energy Not Supplied	0.0318 MWhr/customer. yr

5.3 Adequacy Solution

Due to heavy load demand in comparison to actual generation, load shading or interruption of supply is comes in to the scenario. This is the main reason for higher values of reliability indices as presented in Table 18. Generation inadequacy has widespread catastrophic consequences for both society and its environment. Consequently great emphasis has been placed for ensuring the adequacy and meeting the demands in the power system [30–32].

5.3.1 Reliability improvement by installing distributed generation (DG)

In distribution systems planning, the present trend is the installation of distributed (or local) generators, which are other than central generating stations and installed closer to consumer premises, preferably at the high load density locations. DGs are small modular resources such as, photo voltaic cells, fuel cells and wind turbine generators. Distributed generation (DG) is expected to play an important role in emerging power systems [33]. The reliability of a distribution system may be increased by modifying failure rate and repair time of each section of the network. Such modifications may require additional investments, which in the presence of DG may be mitigated and resulted in annual savings. The time necessary to start the DG should be taken in to account for the reliability evaluation of distribution system. If this time is sufficiently short, the customers suffer a momentary interruption, while if not, they suffer a sustained interruption.

Studies have predicted that DG has significant percentage in new generation. Different resources can be used in DG. Its impact on distribution systems may be either positive or negative depending on the system's operating condition, DGs characteristics and location [33–34]. Potential positive impacts include, improved system reliability, loss reduction and improved power quality.

The work covers several implications of RDG installation on residential, commercial and governmental offices in distribution system for the purpose of providing continuous electric supply, based on high load density locations. In this case, it is observed that the Arbegona area has huge energy demand; therefore the study of distributed generation is concentrated on this area. A system with 400kW PV system, 100kW wind generator and 1465Ah battery backup system is considered and the analysis of the reliability of network is conducted. The reliability rates shown in Table 19 are the mean values, calculated by using IEEE standards.

Figure 14 presents the report generated by ETAP software of load point output for automated and micro grid contained Hawassa substation feeder line 10.

Table 19 Reliability input data of distributed generation components

Component Type	Power Generated	Average Outage Rate (f/yr/km), f_s	Mean Time to Repair (hr), r_s	Switching Time (hr)
PV	400kW	0.696	3.9	1
Wind generator	100kW	0.174	3.9	1

Load Point Output Report

Load Bus			Average Interrupting Rate	Average Outage Duration	Annual Outage Duration	EENS
ID	Load Sector	Connected Bus ID	f / yr	hour	hr / yr	MW hr / yr
L1	Residential	LB1	15.4100	2.70	41.55	2.06
L2	Residential	LB2	15.4100	2.70	41.55	1.24
L3	Residential	LB3	15.47	2.6936	41.67	0.92
L4	Residential	LB4	15.5300	2.69	41.79	1.00
L5	Residential	LB5	15.5900	2.69	41.91	2.43
L6	Residential	LB6	2.4400	2.00	4.88	0.60
L7	Residential	LB7	2.4400	2.00	4.88	0.21
L8	Commercial	LB9	2.9830	2.03	6.05	0.26
L9	Commercial	LB8	2.9850	2.05	6.11	0.42
L10	Industrial	LB10	2.9830	2.03	6.05	0.77
L11	Residential	LB11	2.9830	2.03	6.05	0.49
L12.	Govt. & Inst.	LB12.	11.7730	2.00	23.55	0.38
L13	Residential	LB13	11.7730	2.00	23.55	1.59
L14	Govt. & Inst.	LB14	11.7750	2.00	23.55	5.66
L15	Commercial	LB15	11.8030	2.00	23.61	0.92
L16	Residential	LB16	24.1560	1.57	37.99	1.61
L17	Residential	LB17	24.4260	2.00	48.85	1.04
						21.59

Figure 14 Load point output report for automated and micro grid contained Hawassa 33 kV feeder line 10.

Different system indices of automated and micro grid contained Hawassa 33 kV feeder line 10 is presented in Table 20.

From the above Figure 15, the pink color presents the voltage drop at branch point A-J, which is in an acceptable range. Transformers at the points A, E and G shows pink color that means these transformers are not overloaded, as these are upgraded. By comparing bench mark values it is found that the values of calculated indices presented in table 20, is at satisfactory levels, and are improved significantly by 77.25%, 80.87% and 77.17% for SAIDI, SAIFI and EENS, respectively from the base case.

Table 20 System indices of automated and micro grid contained Hawassa 33kV feeder line 10

System Indices	
SAIFI System Average Interruption Frequency Index	9.0924 f/customer. yr
SAIDI System Average Interruption Duration Index	19.4442hr/customer. yr
CAIDI Customer Average Interruption Duration Index	2.139hr/customer interruption
ASAI Average Service Availability Index	0.9978
ASUI Average Service Unavailability Index	0.00222
EENS Expected Energy Not Supplied	21.392 MW hr/yr
AENS Average Energy Not Supplied	0.0133 MW hr/customer. yr

Figure 15 Single line diagram of modified micro grid contained Hawassa 33 kV feeder 10 line.

5.3.2 Loss of revenue due to power interruption

The loss of revenue cost calculated in this case is 560.05\$, which is less than the previous cases i.e. base case (2530.062\$) and security strategy solution (1382.72\$).

6 Result and Discussion

This work has illustrated serious reliability problem of Hawassa 33kV feeder line 10 and recommended the solutions. This is accomplished through detailed analysis and calculation. Therefore, this work represents a practical problem of Hawassa city distribution network, Ethiopia. Different cases studies are performed under various solution techniques. In base case environment, the reliability of feeder line 10 is very poor, as assessed by the different reliability indices. The calculated value of different reliability indices such as SAIDI, SAIFI, CAIDI, ASAI and EENS are 85.4837 hr/customer, 47.5205 interruptions/customer, 1.799 hr/customer, 0.9902 and 93.706 MWhr/yr, respectively, for base case Hawassa substation 33kV feeder line 10. Higher values of these indices are indicated that the reliability of feeder line 10 is poor. Due to poor reliability the outage cost associated with customers are also very high. The outage cost of energy is $(0.6 * 1000 * 93.706)$ 56223 birr or 2530.062\$. Therefore, to improve the reliability of selected feeder 10, three remedies are proposed by the authors. Further, reliability analysis is performed, which showed that reliability is considerably improved by using propped solutions. The proposed solutions are design, security strategy and adequacy solutions.

6.1 Design Practice

In this method of reliability enhancement, the existing 50mm² conductors are replaced by upgraded 95mm² conductors. Further, the overloaded distribution transformers are replaced by enhanced capacity distribution transformers. The analysis is performed on ETAP software and results are discussed below.

6.1.1 Reliability analysis with design practice

A study has been conducted on the performance and design practice of the Hawassa feeder 10 distribution systems to identify causes for power interruptions. The work has been conducted with field observation and data collection. The collected data includes peak load, type of faults, frequency and duration of interruption of medium voltage (33kV) outgoing feeder of

the distribution system. It is found that over-loading, earth fault and short circuits are the major causes of interruptions in the distribution systems. It is also found that some transformers are over loaded and are not protected from the faults. Most of the interruptions are because of the transformer and related accessories like HRC fuses, oil and drop out fuse. Therefore, it is recommended to upgrade overloaded transformers and to install disconnectors at branching point and drop out fuse near to the distribution transformers. The other most frequent cause of outage is earth fault due to clearance problem. It is identified that Hawassa feeder 10 distribution line is constructed with 50mm² AAC conductor, which has unacceptable voltage drop of 9.99%. This is corrected by re-conductoring the line with new 95mm² AAC conductor, which improves the voltage drop to 4.99%. Further, the calculated short circuit capacity of 50mm² conductor is 7.42kA, which is less than the rated short circuit fault current capacity i.e. 14.009kA. Therefore, for reliability enhancement, replacement of the line with 95mm² conductor with 14.106kA short circuit capacity is performed. A upgraded capacity redesigned system is developed in ETAP software as discussed in the previous section, which shows that voltage drops are within permissible range. Further, by re-conductoring with 95mm² conductor, the rated short circuit fault current capacity i.e. 14.106 kA is also increased and now equal to system's rated short circuit fault current capacity 14.009 kA. Therefore, the reliability is greatly improved by redesigning the system. It is observed that out of 100% interruptions, majority (80.3%) of the interruptions are due to short circuit, earth fault and over load, while 15.52% is due to load shading and the remaining 4.18% is due to line and distribution transformer overload. It is also observed that active and reactive power losses occurred (copper loss of the feeder at full load) in the feeder line 10 with 50mm² AAC conductors are 60.04kW and 11.39kVAr, respectively. Therefore, by re-conductoring with 95mm² AAC conductors, these losses are reduced to 30.2kW and 10kVAr.

6.1.2 Cost benefit analysis with design practice

With higher degree of reliability, investment cost also higher. On the other side, the customer costs associated with customer outages reduces as the reliability increases. The cost incurred due to the replacement of existing 50mm² size conductor by 95 mm² and upgrading the transformer capacity is discussed in this section. For 50mm² conductor, total cost incurred is 65386.09 \$ as total length required is 91.7 km and cost per meter is 0.713\$ for 50 mm² conductor. On the other hand, for 95mm² conductor size, total cost incurred is 109641.31\$

as total length required is 91.7 km and cost per meter is 1.196\$. The installation costs of 50kVA, 100kVA and 200kVA transformers are 7951.56\$, 9948.10\$ and 13281.61\$, respectively. Further, the extra costs incurred for capacity up gradation from 50kVA transformer to 100kVA and 100kVA to 200kVA are 1996.53\$ and 3333.51\$, respectively. Therefore, the total cost required for replacing the 50mm² size conductor with 95mm² and capacity enhancement of three transformers (2 transformers from 50kVA to 100kVA and 1 transformer from 100kVA to 200kVA) are 116967.88\$. The revenue saved by minimizing the interruptions is 1886.43\$ (=2444.48–558.05). Finally, the total revenue required for replacement of conductors and enhancement of transformer capacities is 49695.37\$ (=116967.88–65386.09–1886.43).

6.2 Security Strategies

Under this solution technique, number of faults and fault duration is reduced by using various techniques such as preventive maintenance, monitoring, system automation, system reconfiguration etc. The analysis is performed on ETAP software and results are discussed below.

6.2.1 Reliability analysis with security strategies

The frequency and duration of interruptions for Hawassa feeder 10 distribution networks for 12 months are analyzed. Distribution reliability indices (SAIFI, SAIDI, CAIDI, ASAI and EENS) are calculated and analyzed. Further, calculated distribution reliability indices are compared with benchmark values. From the analysis, an average value of SAIFI, SAIDI, CAIDI, ASAI and EENS are 22.1833 f/customer*year, 46.046 hr/customer*year, 2.076 hr/customer Interruptions, 0.9947 and 51.212 MWh/yr, respectively. By incorporating security strategies in the system, there is an improvement in the reliability of selected feeder by the percentage of 46.13%, 53.32% and 45.35% for SAIDI, SAIFI and EENS, respectively from the base case.

6.2.2 Cost benefit analysis with security strategies

The total outage cost due to interruptions after the incorporation of security strategies in the system is reduced to 1382.724\$, as compared to 2530.062\$ in the base case condition. Therefore, the total reduction in the outage cost after incorporation of security strategies is 1147.338\$.

6.3 Adequacy Solutions

This solution technique incorporated distributed renewable energy generation sources at distribution level for reliability enhancement. In this work modular distributed generation (DG) sources such as photovoltaic (PV), wind turbine generator (WTG) and battery energy storage (BES) are incorporated at Hawassa distribution feeder 10 for enhancing reliability. The analysis is performed on ETAP software and results are discussed below.

6.3.1 Reliability analysis with adequacy solutions

Distribution reliability indices (SAIFI, SAIDI, CAIDI, ASAI and EENS) are calculated and analyzed with distributed generation sources. From the analysis, an average value of SAIFI, SAIDI, CAIDI, ASAI and EENS are 9.0924 f/customer*year, 19.444 hr/customer*year, 2.139 hr/customer Interruptions, 0.9978 and 21.392 MWh/yr, respectively. By incorporating distributed generation sources in the system, there is great improvement in the reliability of selected feeder by 77.25%, 80.87% and 77.17% for SAIDI, SAIFI and EENS, respectively from the base case.

6.3.2 Cost benefit analysis with adequacy solutions (distributed generations)

In this section cost benefit analysis is performed with distributed generation sources.

6.3.2.1 PV generation

Table 21 provides the component price of 400kW PV power generation system.

The total cost of PV generation system is 19478700 birr or 708316.43\$.

Table 21 Component price of 400kW PV power generation

No.	Description	Quantity	Unit Price [Birr]	Total Price [Birr]
1.	Module (250 Wp)	1600	22/Wp	8,800,000
2.	Cabling, Switch, Holder, Plug, Divider and PV panel support structure cost	—	—	10,000
3.	400kW inverter	1	600,000	600,000
4.	Direct cost of equipment	—	—	9,410,000
5.	Installation cost (7% of direct cost of the equipment)			658,700
Total system cost				19478700

6.3.2.2 Wind power generation

Table 22 provides the component price of 100kW wind power generation.

The total cost of all the components of 100kW wind power generation system is 316312.7 birr or 11502.28\$.

6.3.2.3 Battery energy storage system

Table 23 provides the component price of battery energy storage system.

The total cost of all the components of battery energy storage system is 292485 birr or 10635.82\$. Therefore, the total cost associated with DGs is 734785.9\$ (=708316.43+10635.82+11502.28). The total outage cost due to interruptions after the incorporation of DGs in the system is reduced to 560.05\$, which is less than the previous cases i.e. base case (2530.062\$) and security strategies solution (1382.72\$). Therefore, the total reduction in the outage cost after incorporation of DGs with respect to base case is 1970.012\$ per 1000 hours. Thus, the total saving in one year is around 17257.31\$.

Table 22 Component price of 100kW wind power generation

Component Description	Quantity	Component Unit Price (Birr)	Component Total Price (Birr)
Blades (three)	1	29740.11	29740.11
Hub	1	12894.31	12894.31
Pitch mechanisms and bearings	1	7098.8	7098.8
Main shaft	3	4117.86	12353.58
Main shaft bearing and block	3	2329.3	6987.9
Electrometric mounting system	3	540.73	1622.19
Generator isolation mount	3	180.24	540.72
Support structure	3	6,807.64	20422.92
Generator cooling system	3	540.73	1622.19
Brake system hydraulics	3	1,081.46	3244.38
Coupling	3	540.73	1622.19
Nacelle cover	3	3,396.89	10190.67
Generator	3	12006.96	36020.88
Cable	3	3577.13	10731.39
Switch gear	3	2509.54	7528.62
Yaw derive and bearings	3	3230.51	9691.53
Control and safety system	3	1428.08	4284.24
Tower	3	36894.37	110683.11
Foundation	3	9677.67	29033.01
Total cost			316312.7

Table 23 Component price of battery system

No.	Component Description	Unit Price (Birr)	Total Price (Birr)
1	Lead Acid Deep Cycle Battery 4.762Ah of 300 pcs. total 1428.6Ah	974.95	292485

From the above analysis, it is clear that by incorporating DGs in the system, the reliability of the Hawassa distribution system feeder 10 is greatly improved. Therefore, DG installation is the best method for improving the reliability of practical distribution system.

7 Conclusion

The main aim of this work is to identify causes of interruptions and suggest possible solutions to enhance the reliability of Hawassa distribution feeder 10. Furthermore in this work, reliability analysis is performed with proposed solutions for Hawassa distribution systems feeder 10. The collected data for selected distribution network is analyzed in detail to evaluate the reliability of the system. From the substations fault record, it is concluded that mostly the failures in the distribution system are happened due to short circuits, earth faults and over loads (i.e. when generated power is below the total demand, other than blackout). The Hawassa distribution feeder 10 reliability indices (SAIDI, SAIFI, CAIDI and ASAI) for eleven months (January 2015 to November 2015) have been calculated, analyzed and results are stated in this work. The calculated results for SAIDI, SAIFI, CAIDI and ASAI are compared with benchmarks, which verified Hawassa distribution feeder 10 is noncompliance with standards. Furthermore, three potential solutions for the improvement of the reliability of the distribution system are considered. The proposed solutions are design, security (operation) and adequacy for reliability improvement and they are discussed extensively. The result shows the improvement in the reliability of feeder 10. Largest improvement (around 80%) is obtained in the feeder 10 reliability with the incorporation of renewable distributed generations (DGs). Since the location and the size of the renewable DG's greatly affects the reliability of the power systems, finding the optimal size and location of the DG's can be investigated in the future work. Optimization techniques that consider constraints such as the range and location of DG in the distribution network can be also be used for this purpose in the futuristic enhancement of the current study.

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