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Reliability Assessment and Proposing Possible Solutions for Wolayta Power Distribution System

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Abstract: This paper focuses thoroughly to identify the causes for power interruptions that makes the distribution network unreliable and dissatisfies the customers and proposes possible solutions to improve reliability. Deterministic Approach and Probabilistic Approach are used to investigate the reliability of the distribution system. The case study area is Wolayta substation distribution system, Wolayta Sodo city, Ethiopia. The calculation of different reliability indices clearly indicates that Wolayta Sodo distribution substation system is extremely unreliable. The reliability of the existing distribution system is improved by specifying the materials and devices like transformers, insulators, bus bars, grounding system and conductors of 132/33kV. And also improved by connecting small hydro and solar power stations at the customer side.

Keywords: reliability assessment; power interruption; distribution system

1. Introduction

Reliability of power supply is one of the major features of power quality [1]. The two constraints of economics and reliability are competitive because increased reliability of supply generally requires increased capital investment [2]. These two constraints are balanced in many different ways in different countries and by different utilities, although they are all based on various sets of criteria. Reliability assessment is the most important factor in designing and planning of distribution systems that should operate in an economic manner with minimal interruption of customer loads.

Customers require higher quality power because now most of them are having more sensitive equipment and devices. The effectiveness of a power distribution system is measured in terms of efficiency, reliability, and quality [3].

Most of the power interruptions are due to the result of failures in the primary and secondary distribution systems. A highly reliable generation and transmission system may still result in poor energy supply to the customers if the distribution system is unreliable. Therefore, distribution system reliability evaluation is important to ensure appropriate system reliability levels and to provide effective information for regulatory bodies to set proper bench marks.

Reliability is the continuation of power supply without interruption [4, 5]. Simply reliability is the measurement of equipment outage rates and power interruption duration. Some of the events that disrupt normal operation of the distribution system leading to power outages are temporary and permanently faults.

Unreliable power distribution affects daily activity of customers. For industry it reflects in the quality of products as well as lowers their productivity, which in turn reduces their turn over [6]. Over all the customers face frequent interruption and utility has taken long time to alleviate it. Thus, the objective of the study is to assess the reliability of the current distribution system and suggest solutions of reliability improvement.

2. About Wolaiyta Sodo Substation

The current power distribution in Wolayta Sodo substation is radial distribution system type. The basic distribution network model of Wolayta Substation is shown in fig.1. The source of electricity for some areas is from 132kV/15kV/400V, 132kV/33kV/400V, and fed from 132kV/66kV/0.4kV distribution system from the local substation. The system is having 15kV, 33kV and 66kV outgoing feeders.

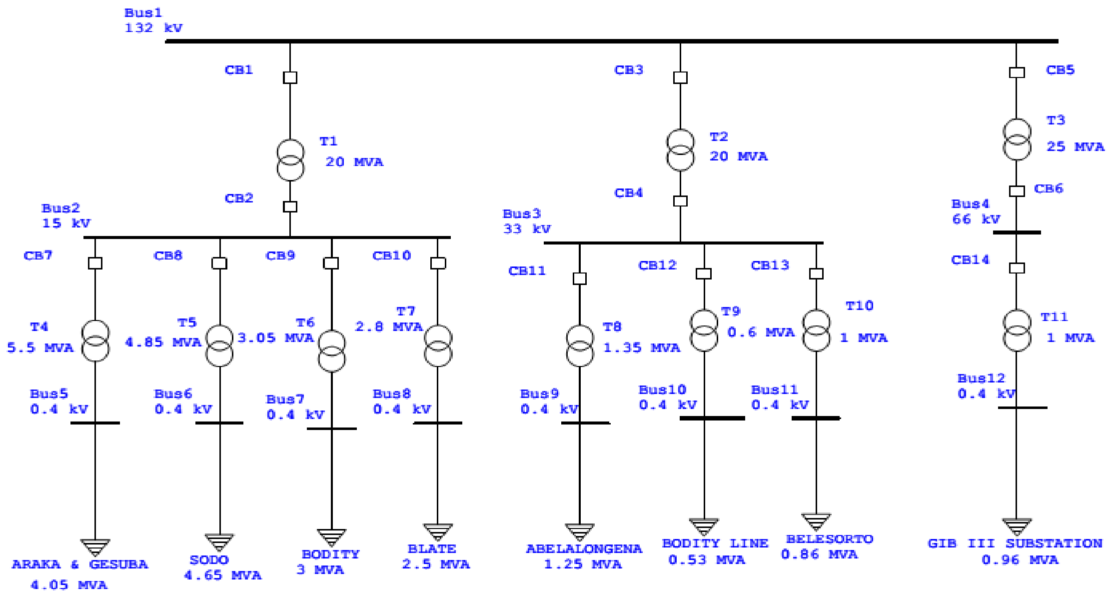

Fig.1. Single line diagram of Wolayta Sodo substation

Table 1 . Feeder specification for Sodo substation

Voltage level	Feeder name	Capacity (MVA)	Feeder load C.T ratio (A)	No. of transformers (kVA)	No. of customers
15/0.4 kV	Line-1	20	150/5	58	5070
	Line-2		300/5	130	12016
	Line-3		150/5	86	3712
	Line-4		150/5	65	581
33/0.4 kV	Line-1	20	75/1	50	352
	Line-2		150/1	16	306
	Line-3		150/1	68	615
66/0.4 kV	Line-1	25	250/1	-	Gives to Gibe-III substation

3. Various factors that cause interruption in Distribution Systems:

The various factors causing interruption are equipment failure, human, animals, extreme weather, trees, and usage of equipment and devices beyond their ratings [7]. The total number of interruptions and durations of one-year data for all the feeders of Wolayta substation are given in Tables 2 and 3 [8].

Table 2. One-year average frequency of interruption of fault types of the substation

Fault type	Months May2016-April 2017, frequency interruption(in number)											
	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	April.
DPEF	74	67	117	56	101	138	92	50	54	97	35	40
DPSC	41	59	60	30	89	83	149	70	49	73	39	50
DTEF	14	22	52	35	32	29	29	10	13	10	15	10
DTSC	27	30	33	17	32	41	21	25	28	13	16	15
TLP	7	13	79	24	20	31	16	10	14	6	0	5
OP	46	66	76	29	65	127	5	50	43	67	35	45
SOL	0	0	0	0	1	0	0	0	0	1	0	0
TOTAL	209	257	417	191	341	449	392	215	201	268	140	165

DPEF – Distribution Permanent Earth Fault
DPSC- Distribution Permanent Short Circuit Fault
DTEF - Distribution Temporary Earth Fault
DTSC - Distribution Temporary Short Circuit Fault
TLP- Transmission Problem
OP- Operation and Maintenance
SOL- Solution Overload

Table: **3.** One-year average frequency of duration of fault types of the Wolayta substation

Fault type	Months May2016-April 2017, frequency interruption(in number)											
	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Janan.	Feb.	Mar.	April
DPEF	137.7	141.5	175.	259.0	316.4	318.9	222.2	200.5	117.7	188.7	184	180
DPSC	76.78	126.2	79.32	21.85	152.9	265.3	648.3	250.5	143.1	258.6	179	160
DTEF	0.84	1.13	4.04	2.29	1.89	1.6	1.79	1.5	0.81	0.65	1.3	1.6
DTSC	1.68	1.8	58.39	1.09	1.84	2.2	1	1.7	1.64	0.76	0.9	1
TLP	4.76	8.84	81.64	4.33	4.57	5.84	39.04	40.6	8.9	1.89	0	30
OP	47.16	59.45	95.74	41.58	77.78	96.05	75	65	37.96	79.9	0	45
SOL	0	0	0	0	1.73	0	0	0	0	0.32	48	1
TOTAL	268.9	338.9	494.2	330.2	557.2	689.9	987.3	559.8	310.1	530.8	441.6	418.6

4. Reliability Indices Evaluation Using Deterministic Approach

Table 4. One -year average value of reliability indices

Feeder name	One year average value of reliability indices								
	SAIFI (int/cus)	SAIDI (Hr./yr.)	CAIDI (Hr./int.)	CAIFI	ASAI (%)	ASUI (%)	MAIFI	ENS (MWh)	ACENS (Birr/year)
1(15kV)	36.00	340.575	9.988	1.67	92.1	7.9	5.6	2016.77	1210060.98
2(15 kV)	27.42	222.66	7.6353	1.27	95.6	4.4	4.5	1633.17	979903.8
3(15 kV)	26.58	184.961	7.352	1.23.	96.2	3.8	5.8	1014.12	608465.29
4(15 kV)	24.83	250.478	10.274	1.71	94.5	5.5	3.9	1131.06	678635.04
1(33 kV)	26.92	399.843	15.596	2.59	91.6	8.4	4.9	881.38	528825.24
2(33 kV)	35.00	455.705	13.483	2.25	90.3	9.7	4.7	373.72	224232.89
3(33 kV)	107.08	1114.78	11.776	1.96	75.4	24.6	21.2	1253.29	751974.18

5. Reliability Indices Evaluation Using Probabilistic Approach

The probabilistic approach to power system reliability analysis views the system as a stochastic process evolving over time. It is categorized as analytical methods and simulation (Monte Carlo simulation) methods [4]. The analytical methods represent the system behavior by mathematical models and evaluate the system reliability using direct numerical solutions. Some of the analytical methods in use are cut set, Markov, and equivalent method. The simulation methods, on the other hand, estimate the system reliability based on simulating a series of random sampling of scenarios and random behavior.

Let λ be the failure rate and μ be the repair rate.

If failures and repairs are exponentially distributed, the probability of a component k on outage at a time t = T, given that it was operating successfully at t = 0, is

$$P_{fk} = \frac{\lambda}{\lambda+\mu} - \frac{\lambda}{\lambda+\mu} e^{-(\lambda+\mu)T} \quad (1)$$

In steady-state condition, i.e., t = ∞, the unavailability or the Forced Outage Rate (FOR) of component k can be obtained as,

$$P_{fk} = \frac{\lambda}{\lambda+\mu} = FOR \quad (2)$$

A(t) = Prob(available at time t), and

$$A(\infty) = \lim_{t\to\infty} A(t) \quad (3)$$

Thus assume that the time to failure, X, is an exponential variable with parameter, λ, so that its density function, f(x), is given by

$$f(x) = \frac{1}{\lambda}\exp\left(\frac{-x}{\lambda}\right), for\ x > 0 \quad (4)$$

The probability of a plant surviving at time t in a constant failure rate environment, is given by

$$R(t) = \exp\left(\frac{-x}{\lambda}\right)$$

The complement of this survival probability is the probability of failure in time t, given by

$$1 - \exp\left(\frac{-x}{\lambda}\right).$$

Similarly assume an exponential model with parameter μ for the time to repair variable Y, so that the density function of Y, g(y), is given by

$$g(x) = \frac{1}{\mu}\exp\left(\frac{-y}{\mu}\right), for\ y > 0 \quad (5)$$

There for using the above exponential models, the instantaneous availability of a power plant is

$$A(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu} e^{(-(\frac{1}{\lambda}+\frac{1}{\mu})t)} \quad (6)$$

The steady state availability is obtained by taking the limit of A(t) as t approaches infinity. This gives

$$A(\infty) = \frac{\mu}{\lambda+\mu} \quad (7)$$

And the instantaneous forced outage rate of a plant is given by:

$$R(t) = \frac{\lambda}{\lambda+\mu} + \frac{\mu}{\lambda+\mu} e^{(-(\frac{1}{\lambda}+\frac{1}{\mu})t)} \quad (8)$$

Then the long-run (steady-state) forced outage is $R(\infty) = \frac{\lambda}{\lambda+\mu}$

Now let $P_{ij}(t)$, (i,j=0,1) be the probability of the transition of state from i to j in a small interval of time t, where 1 denotes ‘up’ and

0, 'down' state in a Markova chain. The instantaneous availability and instantaneous forced outage rate, as obtained above, are nothing but the same state transition probabilities, P_{11} (t) and P_{00} (t) respectively. That is,

P_{11} (t) = A (t), P_{00} (t) =R (t)

The remaining transition probabilities from up to down and from down to up state of the Markova chain:

$$P_{01}(t) = 1 - P_{00}(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu} e^{\left(-\left(\frac{1}{\lambda}+\frac{1}{\mu}\right)t\right)} \quad (9)$$

$$P_{10}(t) = 1 - P_{11}(t) = \frac{\lambda}{\lambda+\mu} + \frac{\mu}{\lambda+\mu} e^{\left(-\left(\frac{1}{\lambda}+\frac{1}{\mu}\right)t\right)} \quad (10)$$

When $t \to \infty$, the probability of Markova chain:

$$\lim_{t\to\infty} P_{00}(t) = P_{00}(\infty) = \lim_{t\to\infty} P_{10}(t) = P_{10}(\infty) = R = \frac{\lambda}{\lambda+\mu} = FOR,$$

$$\lim_{t\to\infty} P_{11}(t) = P_{11}(\infty) = \lim_{t\to\infty} P_{01}(t) = P_{01}(\infty) = A = \frac{\mu}{\lambda+\mu} = \text{Availability rate}$$

Now it can be shown that

$$R = \frac{\lambda}{\lambda+\mu} = \frac{\frac{1}{\mu}}{\frac{1}{\lambda}+\frac{1}{\mu}} = \frac{P_{10}}{P_{10}+P_{01}} \quad (11)$$

$$A = \frac{\mu}{\lambda+\mu} = \frac{\frac{1}{\lambda}}{\frac{1}{\lambda}+\frac{1}{\mu}} = \frac{P_{01}}{P_{10}+P_{01}} \quad (12)$$

The probability of feeder lines failure, Estimation of loss of load probability and loss of load expected and Estimation of loss of load probability and loss of load expected are given in Tables (5-7).

Table 5. The probability of feeder lines failure (LOLP)

Feeder name	No. of faults/ year (f)	Failure rate/year λ(f/yr)	Duration hrs./year	T%(100%=8 760hr/ year)	Avg. Repair time hrs./y(μ)	MTTF 1/λ	MTTR 1/ μ	No. customer per year
1(15kV)	432	0.049	681.15	7.776	0.0778	20.2777	12.8606	5070
2(15kV)	329	0.0376	445.32	5.084	0.0508	26.6261	19.6712	12016
3(15kV)	319	0.0364	369.92	4.223	0.0422	27.4608	23.6804	3712
4(15kV)	298	0.0340	500.95	5.719	0.0572	29.3959	17.4865	581
1(33kV)	323	0.0369	799.68	9.129	0.0913	27.1207	10.9543	352
2(33kV)	420	0.0479	911.41	10.404	0.1040	20.8571	9.61145	306
3(33kV)	1285	0.1467	2229.5	25.452	0.2545	6.81712	3.9290	613

Table 6. Estimation of forced outage rate and availability rate

Feeder name	Forced outage rate R	Forced outage rate R (%)	Availability rate A	Availability rate A (%)
1(15kV)	0.388088	38.80879	0.611912	61.19121
2(15 kV)	0.424889	42.48889	0.575111	57.51111
3(15 kV)	0.463039	46.30394	0.536961	53.69606
4(15 kV)	0.372986	37.29863	0.627014	62.70137
1(33 kV)	0.287703	28.77027	0.712297	71.22973
2(33 kV)	0.315454	31.54543	0.684546	68.45457
3(33 kV)	0.365621	36.5621	0.634379	63.4379

Table 7. Estimation of loss of load probability and loss of load expected

Feeders line kV	Estimation Loss of load probability					
	P_{00}	P_{01}	P_{11}	P_{10}	LOLP capacity available=P_{11}	LOLE=P_{11}*t% (100%=8760hr/year)
P_{00}	P_{01}	P_{11}	P_{10}	LOLP capacity available=P_{11}	LOLE=P_{11}*t% (100%=8760hr/year)	P_{00}
P_{00}	P_{01}	P_{11}	P_{10}	LOLP capacity available=P_{11}	LOLE=P_{11}*t% (100%=8760hr/year)	P_{00}
P_{00}	P_{01}	P_{11}	P_{10}	LOLP capacity available=P_{11}	LOLE=P_{11}*t% (100%=8760hr/year)	P_{00}
P_{00}	P_{01}	P_{11}	P_{10}	LOLP capacity available=P_{11}	LOLE=P_{11}*t% (100%=8760hr/year)	P_{00}
P_{00}	P_{01}	P_{11}	P_{10}	LOLP capacity available=P_{11}	LOLE=P_{11}*t% (100%=8760hr/year)	P_{00}
P_{00}	P_{01}	P_{11}	P_{10}	LOLP capacity available=P_{11}	LOLE=P_{11}*t% (100%=8760hr/year)	P_{00}
P_{00}	P_{01}	P_{11}	P_{10}	LOLP capacity available=P_{11}	LOLE=P_{11}*t% (100%=8760hr/year)	P_{00}
P_{00}	P_{01}	P_{11}	P_{10}	LOLP capacity available=P_{11}	LOLE=P_{11}*t% (100%=8760hr/year)	P_{00}

The calculated and evaluated values of reliability indices of all outgoing feeders of distribution system using the methods of deterministic and probabilistic approach compared with the standard benchmark are given in Table 8.

Table 8. The deterministic and estimated probabilistic reliability indices of the distribution system

Indices	Deterministic Approach (Average)		Probabilistic Approach (Average)		Benchmark With Denmark
SAIFI	40.547619		19.04		0.5
SAIDI	424.1443hr/yr.	18days/yr.	44.93hr. /yr.	2days/yr.	24min/yr.
CAIDI	10.87206hr/yr.	0.5days/yr.	2.36hr. /yrs.	0.08days/yr.	70min/yr.
ASAI	90.84%		99.48%		99.981%
ASUI	9.16%		0.52%		0.019%

From table 8, it is clear that Wolayta substation reliability indices values are far away from the required values. Hence it needs improvement in reliability.

6. Solution Ideas For Reliability Improvement Of The Existing System

This paper proposes a solution to improve reliability based on the following aspects.

6.1. Solutions with Specific and Selected Materials for the Existing System

To improve the reliability this section focuses on two things:

a. Adding of Reserve 132/33kV Transformer

In the substation of Wolayta Sodo especially on the 33kV outgoing feeder, there are lot of interruptions per day. Due to several times interruption in the substation breaker, one day the 132/33kV transformer would be damaged and the whole customers connected to 33kV feeder lines are interrupted, therefore one additional transformer connected is necessary to improve the reliability and to satisfy the customer. It is better to add the reserve transformer, for satisfying the customer as well as to deliver reliable power supply to the customers [9, 10].

b. Specification of Materials in Designing/Constructing of 132/33kV Distribution System

Currently the need of electricity increases from time to time, however the Wolayta Sodo substation distribution system had been long applied. Therefore, depending on the need of electricity supply improved design of distribution must be needed.

The Wolayta Sodo substation distribution system is distributed in radial networks, it is in the worst case. Therefore, improving the distribution system is better for efficient supply and reliability.

The distribution transformers at the majority of locations are without accessories like surge arrestors, dropout fuse (fuse links) and HRC. So, the installed transformer with specified materials and with designed standards is better for improving the reliability of the distribution network and to avoid spare inventory. The kVA ratings of the distribution systems are 25, 50, 100, 200, and 315kVA. The current peak load of the old substation obtained from the Load Dispatch Center is 161.524MW/Year (on May 23, 2017G.C.). For better distribution reliability:

- Medium voltage feeders should be separated by sectionalizer.
- Low voltage feeders should be undergrounded
- Loads or customers should be separated by specifying industrial, commercial and residential consumers.
- Design of distribution system should include reactive power compensators i.e. capacitor banks.

c. Material Selection

Various types of conductor materials are copper, aluminum, copper-clad steel, and steel. Out of all conductor materials copper is the best commonly used equipment for grounding. Because of it has high conductivity, resistant to most underground corrosion, good temperature characteristics and thermal capacity. Hence to improve reliability copper conductors should be used.

d. Design of Bus Bars

By considering the following data to determine the size of a bus-bar for Wolayta Sodo substation:

Rated load capacity of the substation=20MVA+25MVA+16/20MVA
=65 MVA

For 132kV;

Rated current= $I_{Rated} = \frac{S}{V.\sqrt{3}}$

$$= \frac{65MVA}{132KV \times \sqrt{3}}$$

$$= 0.284kA$$

For 33kV;

Rated current= $I_{Rated} = \frac{S}{V.\sqrt{3}} = \frac{65MVA}{33KV \times \sqrt{3}}$

$$= 1.137kA$$

Therefore, the rated standards based on the calculated values are described in table 9 for both 132 kV and 33kV voltage levels.

Table 9. Ratings of 132kV and 33kV bus-bars

Description	Minimum requirements	
	132kV	132kV
Types of bus-bar	Copper	Copper
Rated current	1.25kA	5kA
Rated insulation voltage	1000V	1000V
Rated short time withstand current	65kA	100kA
Conductors a. Bar dimensions Cross sectional area	 90mm*6mm =540mm^2	 2*200mm*6mm =2400mm^2
Resistance	0.036mΩ/m	0.0091mΩ/m
Reactance	0.01mΩ/m	0.0025mΩ/m
Impedance	0.038mΩ/m	0.0094mΩ/m
Voltage drop (line to line at power factor of 0.9)	0.08V/m	0.08V/m

6.2. Analysis of Distributed Generation in Distribution System

The Distributed Generation (DG) in renewable energy relies greatly on renewable resources such as hydro, geothermal, wind speed, solar irradiance, ambient temperature and so forth. Consequently, analyzing the characteristics of renewable resources at the installation location, so as to provide proper models that adequately represent these characteristics, is the first step to facilitate the deployment of the renewable DG into the distribution substation system.

The appropriate selection of DG in this study is based on the peak load of the existing system 5MW DG for 15 and 33kV voltage levels. Therefore, by connecting at the MV bus system and LV bus system the impact of DG in distribution system is described in the simulation result using **ETAP** Software.

Distribution system reliability assessment with DG is an important factor in the entire system operations [11]. The optimal allocation of DG can improve the reliability of the system by serving as backup generation for some specific customers in case system interruption from the utility.

Therefore, the distribution system reliability assessment with DG should be properly optimized; for example failure rate, energy availability, system component failure rates, change in load demand and the DG locations. Integration of DG in the distribution system is positive and negative impact on reliability indices and power quality. The positive impacts included faster restoration service to the customer and reduced voltage sags while the negative impacts could be sympathetic tripping, increased fuse blowing etc.

The appropriate and efficient renewable resource for this thesis work is hydro-power and solar energy. The main reasons for this selection is the selected renewable energy sources are support each other for instant in summer the amount of sunlight reduced but the amount of river flow will increase.

6.2.1 Case Studies of Reliability Assessments

The different case studies are discussed to improve the reliability are given in table 10. Table 10 presents the impact of system indices of all outgoing feeders of 15kV and 33kV for three case studies. By connecting 5MW DG at 0.4kV bus of all feeders is more improvement than the DG installed at the 15kV and 33kV bus lines. It is clearly that significantly improved when the DG is placed close to the customers than near to the supply point. SAIFI and SAIDI are reduced while DG is connected far from supply point. On the other hand CAIDI tends to be slightly higher when distance from supply point increases.

Table 10. Simulation results of 15 and 33kV comparison with the previous results

Indices		Case 1	Case 2	Case 3
		Without DG	DG at 15 and 33kV bus	DG at 0.4kV bus
SAIFI (f/cus.yr)		10.3986	5.0870	0.0771
SAIDI (hr./cus.yr)		88.3726(3.5d/yr.)	44.9033(1.8d/yr.)	4.5169
CAIDI (hr./cus.int)		8.499(0.35d/yr.)	8.827(0.36d/yr.)	58.564
ASAI (%)		98.99	99.49	99.95
ASUI (%)		1.01	0.513	0.05
EENS (MWh/yr.)		1203.766	517.237	64.654
AENS(MWh/cus.yr)		171.967	86.2062	9.236
ACENS	(ETB)	722,259.60	310,342.2	38,792.4
	USD (1ETB = 0.0365163 USD)	26,374.28	11,332.56	1,416.56

The lower EENS, AENS and ACENS is obtained when the DG units at 0.4 kV bus than DG units at 15kV & 33kV bus installed, and Table 10 also shows the reliability index between the base case and mitigated case this result as the annual worth of placing a DG unit at 15kV, 33kV and 0.4 kV buses.

Simulation result of the average and annual outage duration of all feeder lines of the distribution system, depending on three case studies are compared with the current available outage durations are given in Table 11.

Table 11. Simulation results of 15 and 33kV comparison with the previous results

Feeder Name	case 1	case 2	case3
	Annual outage Duration in hrs./year	Annual outage Duration in hrs./year	Annual outage Duration in hrs./year
1(15kV)	75.54	5.01	4.62
2(15kV)	91.54	5.01	4.62
3(15kV)	83.54	5.01	4.62
4(15kV)	71.54	5.01	4.62
1(33kV)	91.39	5.01	4.62
2(33kV)	99.39	5.01	4.62
3(33kV)	107.39	5.01	4.62

Table 11 presents the impact of average and annual outage duration of all feeders of 15kV and 33kV for three cases. The Annual outage duration is reduced while DG is far from supply point. On the other hand average outage duration tends to be slightly higher when distance from supply point increases.

7. Result and Conclusion

The average reliability indices of the case study area are SAIFI, SAIDI, CAIDI, ASIAI, ASUI, EENS, AENS and ACENS are 283.83failure/customer/yr,2960.01h/customer/year , 76.10hr/customer/interruption, 98.749%, 1.251%, 8303.49MWh/year, 1186.21MWh/customer/year and 4,982,094.00ETB(216,290.377USD) respectively.

To limit the scope of the study, the proposed solutions of the distribution system based on the specification and selection of the materials for designing and constructing the power distribution network 132/33kV, 20MVA capacity transformer are 132kV conductor size 3×95mm^2 carrying load current 300A, short circuit current 4.37kA, its acceptable short circuit current value is 15.69kA and voltage drop 9.64%, and 33kV conductor size 3×185mm^2 carrying load current 463A, short circuit current 17.5kA its acceptable short circuit current value is 30.55kA and voltage drop 3.64%.

Also the acceptable values of distribution grounding design are earth current conductor size is 300mm^2, touch attainable voltage is 2.038V, step attainable voltage is 3.07V, touch tolerable voltage is 278.81V, and step tolerable voltage is 713.39V respectively.

Also the annual outage duration is reduced while DG is far from supply point. On the other hand average outage duration tends to be slightly higher when distance from supply point increases.

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