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STUDY OF POWER SYSTEM RELIABILITY AND IMPROVEMENT POTENTIAL BY USING DISTRIBUTED GENERATION

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Keywords:

Distributed Generation;
Reliability;
DG location
Energy not suplied;
Powerfactory software;

Abstract *The power distribution system in many developing countries has a serious problem of supplying electricity in reliable way. Power interruptions are frequent and long lasting in many of the African developing countries including Ethiopia. This has caused a major economic and social problems. The main purpose of this paper is to evaluate the power reliability of a city in Ethiopia and the potential impacts of Distributed Generation (DG) units on mitigating the power system reliability problem of the network. Distributed power generations are commonly used in distribution system to reduce the power disruption in the power system network which results in a considerable reduction in the total power loss in the system and reliability performances. It is also important to place distributed generation with the right size at an optimal location so that the purpose of power loss minimization and reliability improvement is served on the feeders. Therefore, this study presents the assessment result of the power distributionreliability for Bishoftu city distribution substation and the potential of using distributed generation for improving the urgent andpressing power interruption problems at the area.The new Digsilent power factory software has been used to simulate and verify the improvement of thereliability indices for the distribution system.*

I.Introduction

Bishoftu city is located in East Shewa zone of Oromia in Ethiopia and its geographical coordinates are 9° 6' 0" North, 37° 15' 0" East. Since the location of Bishoftu city is near to the capital city (Addis Ababa), the Ethiopian government selects the city to be one of the industry zones in the country. Bishoftu substation II supplies the city and small towns around Bishoftu including Dire, Amerti, Minjar, partially Dukem and many other industries. Bishoftu city is one of the rapidly growing city and a preferred location for most of the industries being constructed. As a result, considerable share of the electric power demand is directed towards the city. But, electric power interruption is a day to day phenomenon in the area. Power outages have severe negative impact on the social and economic lives of the people. Some of the impacts include loss of production, loss of sales, damages of equipment, spoiled goods and interruption of services of telecommunication systems, banks and others. Reliable electricity is key input for the industrial development and good-living of the people and thus, evaluating the use of DG to alleviate these problems is the motivation for this research undertaking. Saifur Rahman et el [1]**,** with the paper entitled "Impacts of Distributed Generation on the Residential Distribution Network Operation" describe reliability worth assessment of DG at supply point for improving system reliability. Another paper by V. H. M Quezada and J. R., Roman T. [2]**,** entitled "Assessment of energy distribution losses for increasing penetration of distributed generation"examined the amount of losses experienced with increasing penetrations of DG sources.

II. Reliability Assessment of Bishoftu City

The Bishoftu substation is connected to Kality substation with the incoming three-phase transmission line of 132 kV. The installed capacity of the substation is 88 MVA and the substation consists of three power transformers which steps-down the 132 kV to 15 kV distribution voltage levels. This voltage is further stepped-down to customer level voltage of 400/220 volts at the load points. The substation with its thirteen outgoing feeders is shown in in Fig. 1 below.

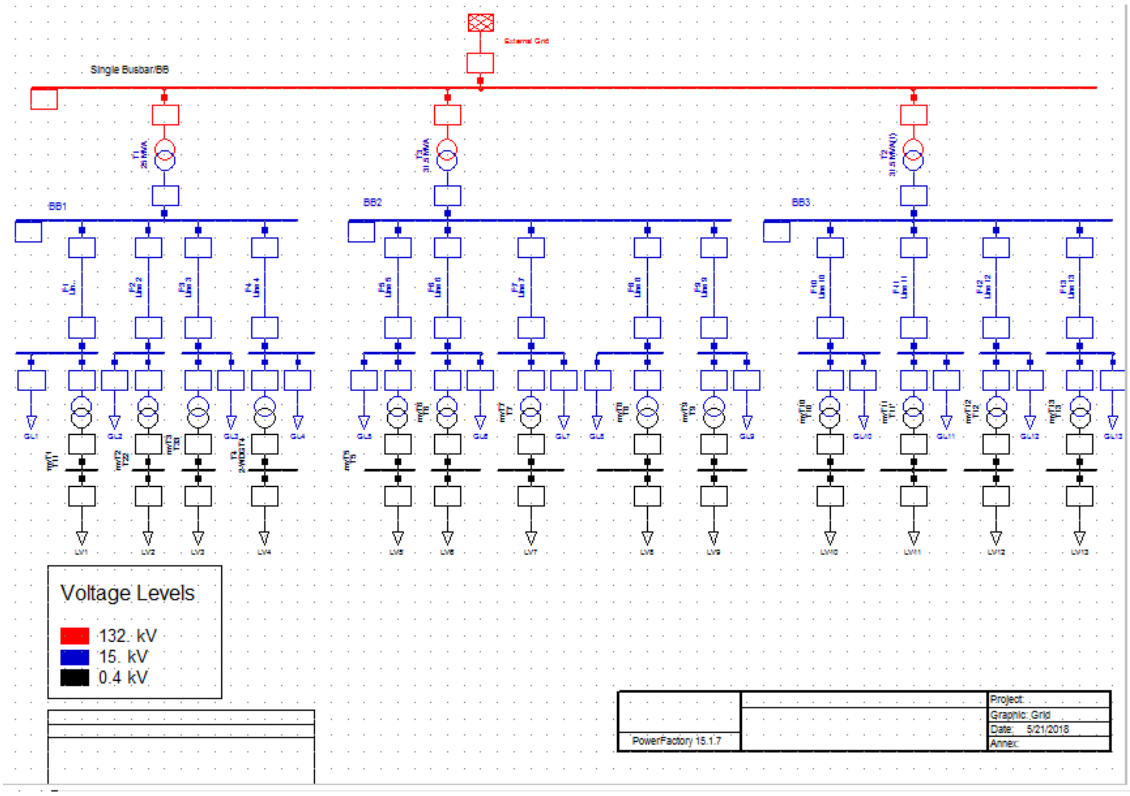

Figure 1 One line diagram of Bishoftu distribution substation

To evaluate the system reliability, the electric utility industry has developed several performance measures. These reliability indices include measures of outage duration, frequency of outages, system availability and response time. The following common reliability indices that are defined in IEEE Standard 1366 have been used to evaluate the system reliability of the distribution substation.

A) Customer Oriented indices

1) System Average Interruption Frequency Index (SAIFI): System Average Interruption Frequency Index (SAIFI), in units of [1/C/a (customer/annum)], shows how often the average Customer experiences a sustained interruption during the period specified in the calculation [3].

$$SAIFI = \frac{\sum \lambda_i N_i}{N_T} \tag{1}$$

Where: λ_i is the failure rate at load point i, N_i is the total number of customer interrupted at load point i, N_T is the total number of customers at load point i.

2) System Average Interruption Duration Index (SAIDI): System Average Interruption Duration Index, in units of [Hr/C/a], indicates the total duration of interruption for the average customer during the period in the calculation.

$$SAIDI = \frac{\sum U_i * N_i}{N_T} \quad (2)$$

Where: U_i= restoration time, [hrs], N_i=Total numbers of customers interrupted, N_T=Total numbers of customers.

3) Customer Average Interruption Duration Index (CAIDI): Customer Average Interruption Duration Index, in units of [hrs], is the sum of customer interruption durations divided by the total number of customer interruptions.

$$CAIDI = \frac{\sum U_i * N_i}{\sum \lambda_i * N_i} = \frac{SAIDI}{SAIFI} \quad (3)$$

Where: λ_i= Failure rate at load point *I* $[hrs]^{-1}$, U_i=outage time at load point i, N_i=Total numbers of customers interrupted.

4) Average Service Availability Index (ASAI): The index that represents the fraction of time (often in percentage) that a customer has power provided during one year or the defined reporting period.

$$ASAI = \left[1 - \frac{\sum U_i N_i}{\sum N_T * T}\right] * 100 \quad (4)$$

Where: T=Time period under study in Hr, U_i=restoration time, in hour, N_i=Total number of customer interrupted at load point *i* andN_T=Total number of customer served.

5) Average Service Unavailability Index (ASUI): This index is the probability of having loads unsupplied and it is the complementary value to the average service availability index (ASAI).

$$ASUI = \frac{\sum U_i N_i}{\sum N_i * 8760} \quad (5)$$

B) Energy-Oriented Indices

1) Energy Not Supplied Index (ENS): Energy Not Supplied, in units of [MWh/a], is the total amount of energy on average not delivered to the system loads [3].

$$AENS = \sum La(i) U_i \quad (6)$$

Where: La (i) is the average load

2) Average Energy Not Supplied Index (AENS): Average Energy Not Supplied, in units of [MWh/Ca], is the average amount of energy not supplied, for the customers [4].

$$AENS = \frac{\sum La(i) * U_i}{N_T} \tag{7}$$

The major faults occurring frequently in Bishoftu substation are short circuit, earth fault and over loading. As usual, only data on sustained interruptions is reported to the regulatory authority specifically permanent fault that being caused by equipment malfunction, cable failure and persistent tree contact. Accordingly, the annual average frequency and duration of interruption data for the three years from 2015 to 2017 for Bishoftu distribution substation are shown in Table 1.

Table 1 Average interruption frequency and duration

Feeder	**Frequency of Interruption (Int/yr.)**			**Duration of Interruption (Hrs. /yr.)**		
	Planned	Unplanned	Total	Planned	Unplanned	Total
L1	11	29.66	40.66	14.41	60.4	74.81
L2	32	30	62	13.01	197.7	210.7
L3	140.67	321.3	461.9	101.93	229.78	331.7
K1	9.33	19.33	28.66	24.86	82.09	106.9
K2	8	18	26	22.44	142.49	164.9
K6	6	7.66	13.66	28.83	12.37	42.2
K7	119	206	325	156.2	151.16	307.3
K8	212.66	232	444.7	152.76	417.69	570.5
K9	207.33	311.33	518.2	168.1	339.24	507.3
K12	6.33	6.33	12.66	3.92	9.17	13.09
K13	10	37	47	10.64	16.38	27.02
K14	84.33	123	207.3	86.17	290.44	376.6
K15	81.66	66.33	148	62.17	124.45	186.6
Syst.	71.41	108.3	179.7	65.03	159.48	224.5

The annual average energy and power consumption of each incoming feeders bus at Bishoftu distribution system is shown in Table 2 below. This annual average energy is calculated from the recorded data for the years from 2015 to 2017.

Table 2 Annual average energy and power consumption of incoming feeder

Feeders (15 kV)	Average energy consumption		Average power consumption	
	Active (MWh)	Reactive (MVArh)	Active (MW)	Reactive (MVAr)
BB1(K5)	21766.1	6829.7	10.65	5.55
BB2(K10)	7936.5	867.5	14.47	5.59
BB3(K15)	76362.8	418.5	12.63	7.41
Overall system	106,065.5	11883.1	37.75	15.55

The number of customers of the city distribution substation with the outgoing feeders are listed and shown below in Table 3.

Table 3 Number of customers on the feeders

Feeders	Residential	Commercial	Industrial	Total
L1	-	-	1	1
L2	-	-	8	8
L3	799	74	6	879
K1	-	-	1	1
K2	-	-	1	1
K6	3300	152	1	3362
K7	-	-	7	7
K8	69	9	7	85
K9	5128	1	12	5141
K12	-	-	1	1
K13	-	-	1	1
K14	1452	27	6	1485
K15	3250	643	74	3967
System	13998	906	125	15025

Table 4 and Table 5 below shows the calculated average customer oriented and energy oriented indices respectively for the feeders by using the equations defined in IEEE Standard 1366 [5] on the basis of data collected for the years from 2015 to 2017 for the particular distribution substation.

Table 4 Annual average customer oriented reliability indices for the feeders at the substation

Feeder	SAIFI	SAIDI	CAIDI	ASAI	ASUI
L1	40.66	74.8	1.8396	99.1461	0.853881
L2	62	210.71	3.3985	97.5946	2.405365
L3	461.97	331.71	0.718	96.2133	3.786643
K1	28.66	106.96	3.732	98.7789	1.221004
K2	26	164.93	6.3434	98.1172	1.882762
K6	13.66	42.2	3.0893	99.5182	0.481735
K7	325	307.31	0.9455	96.4918	3.508105
K8	444.66	570.45	1.2828	93.488	6.511986
K9	518.66	507.34	0.9781	94.2084	5.791552
K12	12.66	13.09	1.0339	99.8505	0.149429
K13	47	27.02	0.5748	99.6915	0.308447
K14	207.33	376.61	1.8164	95.7007	4.2992
K15	148	186.62	1.2609	97.8696	2.130365
Syst.	**179.71**	**224.59**	**1.2497**	**97.4361**	**2.56388**

Table 5 Annual average energy oriented reliability indices for the feeders at the substation

Feeder	P_{peak} (Mw)	ENS (MWh)	AENS (MWh/ca)	EIC ($/yr)	P_{peak} (Mw)
L1	5.04	377.0	377.0	7460.6717	5.04
L2	3.53	743.1	92.9	14719.927	3.53
L3	5.31	1761.4	2.0	34857.712	5.31
K1	5.41	578.7	578.6	11451.555	5.41
K2	4.09	674.6	674.6	13349.616	4.09
K6	4.11	173.4	0.05	3432.4172	4.11
K7	5.14	1579.6	225.75	31259.758	5.14
K8	4.97	2835.1	33.4	56107.351	4.97
K9	5.11	2592.5	0.50	51305.721	5.11
K12	3.92	51.3	51.3	1015.4803	3.92
K13	5.1	137.8	137.8	2727.1016	5.1
K14	4.83	1819.0	1.2	35998.53	4.83
K15	5.81	1084.2	0.27	21457.549	5.81
Syst.	**62.3**	**13,991.9**	**1753**	**276,900.83**	**62.3**

Based on the above data analysis and observations, the following general conclusion can be drawn:

- The reliability of Bishoftu city substation does not meet the requirements set by the regulatory body, which means the Ethiopia Electric Agency (EEA).

- The feeders K-7, K-8, L-3 and K-9 have been identified as feeders experiencing longer interruption duration and frequency.
- Due to both planned and unplanned power outage at the substation, there is large amount of energy not supplied from the system feeders to the customer.

Table 6 below shows the comparison of the most commonly used reliability indices (i.e. SAIFI and SAIDI) with local and other selected countries' standards [7].

Table 6 Comparison of the reliability indices with different standards

Country	**SAIFI (1/c/a)**	**SAIDI (Hr/c/a)**
Canada	3.4	0
Spain	2.2	1.7
USA	1.5	2.3
Ethiopia	20	25
Bishoftu distribution substation	**179.7**	**224.5**

From Table 6 above, it can be observed that the calculated value of SAIFI and SAIDI of Bishoftu substation are above the acceptable national and international standards by large margin. Hence, this clearly verifies that there is a serious reliability problem in the current Bishoftu distribution substation.

To improve the power reliability, the use of distributed generation is proposed and its potential impact on the reliability of the distribution system is evaluated by using the new DigSilent Power Factory version 15.1.7 software. DG technologycanprovidevaluablebenefits for both the consumersandtheelectric distribution systems when optimally located and sized. A great number of benefits are arising from the use of DG, if it is integrated optimally in terms of location and size in the distribution grid[6].

Table 7 and Table 8 below shows the stochastic failure models for each component used as an input variable for the simulation of the system.

Table 7 Stochastic failure parameters for transformers and busbars

Transformer stochastic model			
Components	**Failure frequency (1/a)**		**Repair time (Hr.)**
Transformer: 132/15 kV	0.004		2
Transformer: 15/0.4 kV	0.005		6
Busbar stochastic model			
Bus name	**Failure frequency (1/a)**	**Additional failure per connection (1/a)**	**Repair time (Hr.)**

Busbar: 132 kV	19	4	0.2
Busbar: 15 kV	28	9	2
Busbar: 0.4 kV	23	4	7

Table 8 Reliability parameters of the feeders for the stochastic model

Line No	Failure frequency (1/a*km)	Repair duration (Hr)	Transient fault frequency (1/a*km)
1-K1	8	4	1
2-K2	6	3	1
3-K6	6	2	4
4-K7	3	2	6
5-L1	7	4	1
6-L2	12	9	12
7-L3	10	22	14
8-K8	22	7	6
9-K9	12	9	1
10-K12	22	7	6
11-K13	20	20	1
12-K14	13	6	4
13-K15	11	8	2

In order to validate the research results, the existing network modeled in Figure 1 of section II above is simulated for its reliability performance using the Digsilent power factory softwareand the screenshot of the simulation result is shown in Table 9. This simulation result is obtained without adding any modification to the existing network.

Table 9 Simulated reliability indices for the existing network

```
Study Case: Study Case
System Summary
System Average Interruption Frequency Index      : SAIFI =  179.612866 1/Ca
Customer Average Interruption Frequency Index    : CAIFI =  179.612866 1/Ca
System Average Interruption Duration Index       : SAIDI =  276.585    h/Ca
Customer Average Interruption Duration Index     : CAIDI =    1.540    h
Average Service Availability Index               : ASAI  =    0.9684264230
Average Service Unavailability Index             : ASUI  =    0.0315735770
Energy Not Supplied                              : ENS   = 5666.366    MWh/a
Average Energy Not Supplied                      : AENS  =    0.286    MWh/Ca
Average Customer Curtailment Index               : ACCI  =    0.286    MWh/Ca
Expected Interruption Cost                       : EIC   =    2.920    M$/a
Interrupted Energy Assessment Rate               : IEAR  =    0.515    $/kWh
System energy shed                               : SES   =    0.000    MWh/a
Average System Interruption Frequency Index      : ASIFI =  192.604216 1/a
Average System Interruption Duration Index       : ASIDI =  320.615116 h/a
Momentary Average Interruption Frequency Index   : MAIFI =    0.000000 1/Ca
```

As can be observed, the result of the simulation matches very well with the values of the reliability indices calculated from the base interruption data.

IV. Assessment of Reliability Improvement Models

In order to improve the power reliability of the distribution systems, the network is modeled by integrating DGs in the system at the 15 kV and 0.4 kV buses for most interruption affected feeders (K-7, K-8, K-9 and L-3) as shown in Figure 2. The capacity of DG is determined by gradually increasing its capacity in small incremental steps (0.5MW) until the thermal limit or voltage profile of the network at the coupling point is violated.

Case 1: Simulation results when 3 MW DG unit is installed at 15 kV feeders (K-7, K-8, K-9 and L3)

The change is that, the existing system is connected with DG units at the 15 kV bus for the most interruption affected feeders (K-7, K-8, K-9 and L-3) as shown in the single line diagram below (Figure 2). The reliability improvement after DG connection is shown on the output window of the software which is indicated in Table 10 below. The result of the simulation shows that the overall improvement on the indices SAIFI, SAIDI and ENS is 46.5%, 9.1% and 18.7% respectively.

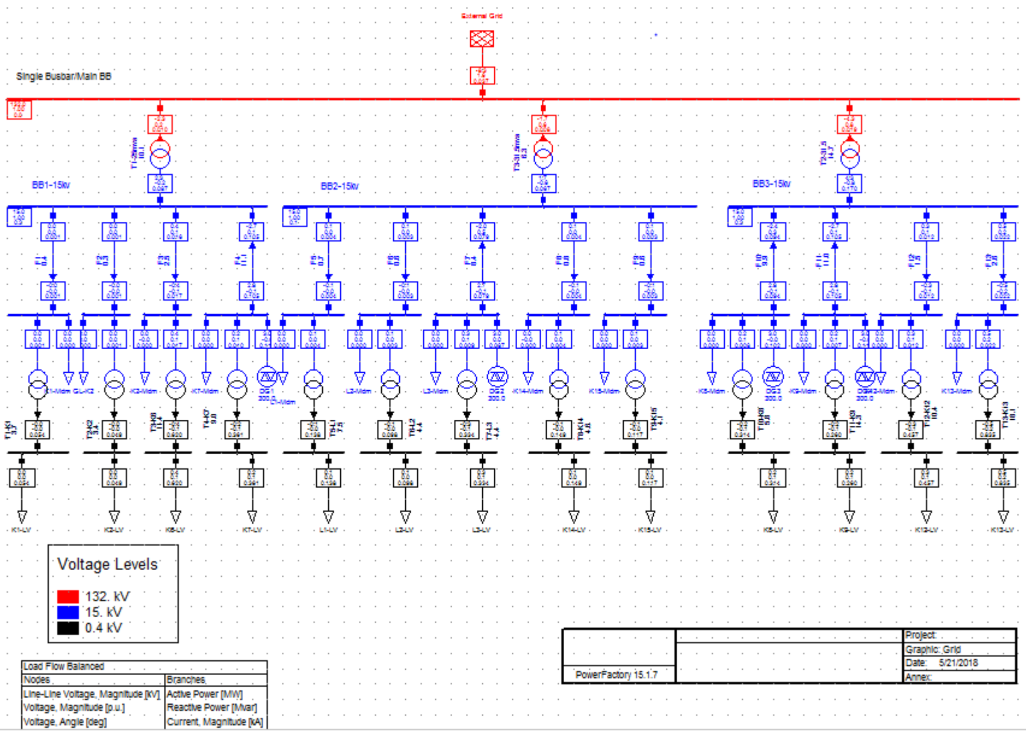

Figure 2: The simulated distribution substation with DG at 15 kV of feeders (K7, K8, K9 and L3)

Table 10 Simulation result of system reliability indices with DG unit at 15 kV busbar

Study Case: Study Case		Annex: / 1
System Summary		
System Average Interruption Frequency Index	: SAIFI =	96.304275 1/Ca
Customer Average Interruption Frequency Index	: CAIFI =	96.304275 1/Ca
System Average Interruption Duration Index	: SAIDI =	251.412 h/Ca
Customer Average Interruption Duration Index	: CAIDI =	2.611 h
Average Service Availability Index	: ASAI =	0.9713000307
Average Service Unavailability Index	: ASUI =	0.0286999693
Energy Not Supplied	: ENS =	4604.654 MWh/a
Average Energy Not Supplied	: AENS =	0.257 MWh/Ca
Average Customer Curtailment Index	: ACCI =	0.257 MWh/Ca
Expected Interruption Cost	: EIC =	1.413 M$/a
Interrupted Energy Assessment Rate	: IEAR =	0.307 $/kWh
System energy shed	: SES =	0.000 MWh/a
Average System Interruption Frequency Index	: ASIFI =	107.870438 1/a
Average System Interruption Duration Index	: ASIDI =	296.932320 h/a
Momentary Average Interruption Frequency Index	: MAIFI =	0.000000 1/Ca

Case 2: In this case study, a 3 MW DG unit is connected at low voltage sides (15/0.4 kV) i.e. 0.4 kV busbars of the feeders (K-7, K-8, K-9 and L-3), as shown in the single line diagram of Fig. 3 below and simulation isconducted on the model. The overall reliability indices improvement with DG connection is shown from the output window of the simulation in Table 11 below.

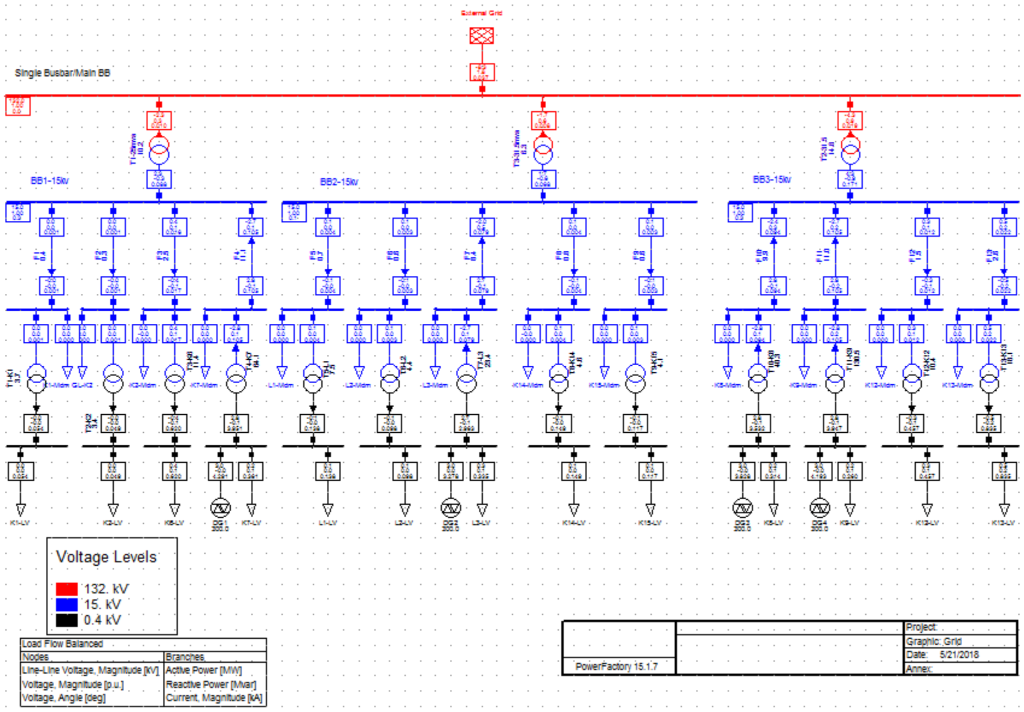

Figure 3: The simulated distribution substation with DG at 0.4 kV of feeders (K7, K8, K9 and L3)

Table 11: Simulation output of system reliability indices with DG at all 0.4 kV

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| Study Case: Study Case                                              | Annex:          / 1 |
| System Summary                                                                          |
| System Average Interruption Frequency Index     :  SAIFI  =  13.767436 1/Ca             |
| Customer Average Interruption Frequency Index   :  CAIFI  =  13.767436 1/Ca             |
| System Average Interruption Duration Index      :  SAIDI  =  30.546    h/Ca             |
| Customer Average Interruption Duration Index    :  CAIDI  =   2.219    h                |
| Average Service Availability Index              :  ASAI   =   0.9965130662             |
| Average Service Unavailability Index            :  ASUI   =   0.0034869338             |
| Energy Not Supplied                             :  ENS    = 128.327    MWh/a           |
| Average Energy Not Supplied                     :  AENS   =   0.018    MWh/Ca          |
| Average Customer Curtailment Index              :  ACCI   =   0.019    MWh/Ca          |
| Expected Interruption Cost                      :  EIC    =   0.069    M$/a            |
| Interrupted Energy Assessment Rate              :  IEAR   =   0.534    $/kWh           |
| System energy shed                              :  SES    =   0.000    MWh/a           |
| Average System Interruption Frequency Index     :  ASIFI  =  16.204548 1/a              |
| Average System Interruption Duration Index      :  ASIDI  =  50.854262 h/a              |
| Momentary Average Interruption Frequency Index  :  MAIFI  =   0.000000 1/Ca             |
```

Table 11 shows the improvement in SAIFI, SAIDI and ENS which is 92.335%, 88.956% and 97.735% respectively with the DG connection on the LV side. Hence, the improvement in the reliability indices is more remarkable compared to the previous case, as the DG is installed closer to the loads.

V. Results and Analysis

It can be seen from Table 8 above that, at the base case the system reliability is poor as the indices value is very large. When DG is installed at 15 kV, the reliability indices are slightly improved. Similarly, as the DG is installed at 0.4 kV feeder side, the reliability of the system is significantly improved with a greater percentage. This is because placing the DG at the end of the line i.e. near to the load point provides capability to pick up the load. This result is summarized in the Table 12.

Table 12: Comparison of simulated results of the base case and modified case system

Indices	Base case	DG @15 kV		DG @ 0.4 kV	
		Reliability values	Improvement in %	Reliability indices values	Improvement in %
SAIFI (1/C/a)	179.6	96.3	46.5	13.8	92.3
SAIDI (Hr/C/a)	276.6	251.4	9.1	30.5	88.9
ENS (MWh/a)	5666.4	4604.6	18.7	128.3	97.7

The simulation result shows clearly the significant improvement of power reliability with an optimal location and size of distributed generations.

VI. Conclusion

The study has shown that the reliability of the Bishoftu substation II is far behind the requirements set by the Ethiopian Electric Agency (EEA). The average frequency of interruptions of the substation is 179.6 interruptions per customer per year and the average duration of interruptions is 276.6 hours per customer per year. There is high unavailability of electric power in the distribution network due to poor system reliability. In the base case study, there is a huge loss of unsupplied energy due to planned and unplanned outages with an ENS of 5666.4 MWh/a and this results in revenue losses of around 2.92 million $/a from the substation. The system is then modeled with DGs.DGs were connected to the four feeders (K-7, K-8, K-9 and L-3) with most serious interruption record. The installation of DG at 0.4 kV buses of the feeders led to 92.3% improvement in SAIFI value, 88.9% improvement in SAIDI value and 97.7% improvement in ENS value. ENS is reduced from 5666.3 MWh/a to 128.3 MWh/a and EIC is reduced from 2.920 million $/a to 0.741 million $/a with average revenue saving of about 2.179 million $/a. Thus, Ethiopian Electric Utility (EEU) can increase its revenue by 74.623% for that area by installing the DG in the distribution network.

All praises and thanks are to the almighty God Jesus Christ, the lord of the world, the most beneficent and merciful for helping me to accomplish this work.

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