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Predicting Reliability of Electric Power Distribution Grid Using Historical Outage Data

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Abstract: Demand for energy is on the increase posing serious complexity issues to power systems in general impacting reliability negatively. The electric power distribution grid is one of the most important entities in a power system contributing up to 90% of reliability problems. Reliability of the electric service provided to end users or load points can be altered by the faults originated either inside or outside of the functional zones of an electric power distribution grid. Reliability analyses of electric power systems in general is based on historical analysis approach where the historical outage data is used to assess the reliability performance of the generation, transmission or the distribution component of the power system. This approach even though gives the appropriate reliability indices indicating the performance of the electric power system component under consideration; however, the computed reliability indices are usually historic making any improvement decision(s) taken to be reactive. In this research article, the historical outage data is rather used to predict the performance of the electric power distribution grid into its future operations and maintenance activities. Analysis of predictive reliability (PR) normally helps in determining the performance state that the design, planning, and operation of the grid will attain when certain reliability objectives and associated performance outcomes are met. The PR is conducted by computing reliability indices using present fault rates, outage durations and number of affected customers. The predicted SAIFI, SAIDI, CAIDI, CAIFI and ASAI values of the years 2020, 2025, and 2030 gave an indication that the reliability of the electric power distribution grid within the metropolis would see varying monthly but improved yearly performances. Better performances regarding these indices are envisaged as the years advance towards the year 2030.

Keywords: Distribution Grid, Predictive, Outage Data, Reliability Indices, Reliability Analysis

1. Introduction

Energy in general, is the prime mover of economic growth and development. There is a direct correlation between the degree of economic development and per capita consumption of energy. Countries with abundant supply of energy have realized substantially higher rates of industrial growth and corresponding increase in gross national product. The world is so dependent on electricity in the 21st century that any interruption or failure in the electric service system could lead to major disruption of daily life and economic losses. As energy sets the basic foundation for the economic development of a country, the energy consumption is bound to grow over the years. Electric power system is one of the largest and the most complex systems established by mankind. Electricity produced and delivered to customers through generation, transmission and distribution systems, constitutes one of the largest consumer markets in the world. The benefits of electric power systems are integrated into the much faster modern life in such extent that it is impossible to imagine society without electrical energy.

A reliable distribution grid is essential for uninterrupted supply of electrical energy. The basic function of a power system is to supply its customers with electrical energy as economically and as reliably as possible. Reliable electric power systems serve customer loads without interruptions in supply voltage. Generation facilities must produce enough power to meet customer demand. Transmission systems must transport bulk power over long distances without overheating or jeopardising system stability. Distribution systems must deliver electricity to each customer's service entrance. In the context of reliability, generation, transmission and distribution are referred to as functional zones.

The distribution segment though vital, has been the weakest link between the source of supply and the customer load points. In many cases, distribution systems are radial in nature and that makes them vulnerable to customer interruptions due to a single outage event. A radial distribution circuit generally uses main feeders and lateral distributors to supply customer energy requirements. In the past, the distribution segment of a power system received considerably less attention in terms of reliability planning compared to generation and transmission segments. The basic reason behind this is the fact that generation and transmission segments are very capital intensive, and outages in these segments can cause widespread catastrophic economic consequences for society. This emphasizes the importance of power systems' reliability. The electric power distribution system accounts for 80% to 90% of all customer reliability problems, hence, improving distribution system reliability is the key to improving customer power supply reliability. One of the major challenges to electric utilities is to increase the market value of the services they provide with the right amount of reliability and to lower their costs of operation, maintenance, and construction to provide customers with electricity at lower rates. For any power system supplying a specific mix of customers, there is an optimum value of reliability that would result in lowest combined costs [1-4]. Vrana and Johansson (2011) maintained that in reliability analysis, power quality issues are usually disregarded. Electric power is seen to be either delivered within acceptable quality limits, or not supplied [5].

Reliability of the electric service provided to end users can be altered by the faults originated either inside or outside of the functional zones of an electric power distribution system. Sustained interruptions, momentary interruptions and voltage sags are three major attributes of the reliability of electric power delivered to the customer [6]. A sustained interruption is referred to the situation where the electric service is interrupted for a long period of time, normally for a time greater than one minute, which is a reliability issue. A momentary interruption is a brief disruption in the electric service, usually lasting not longer than a few minutes, which is a power quality issue [3]. The maximum duration of a momentary interruption varies from utility to utility, but it is typically between one and five minutes. In the past, the momentary interruptions were not as noticeable to customers as they are today. In addition, today customers use sensitive equipment that can even be sensitive to the slightest variations in the supply voltage, transients, abnormal waveforms, and harmonic distortions. Voltage sag is a significant power quality issue that can affect the majority of sensitive equipment like personal computers, adjustable speed drives, programmable logic controllers, semiconductor devices and contactors [6]. The concept of reliability in the electric power system may be interpreted using three different concepts, namely adequacy which is the capability of the system to meet its demand at all times considering scheduled and expected unscheduled outage of the elements; security which refers to the ability of the system to withstand sudden disturbances such as a short circuit; and quality with respect to voltage condition, and harmonic characteristics, etc.

It should be noted that the definition of reliability may vary from different perspectives. The two main perspectives for reliability consideration of an electric power system are customer perspective and utility perspective. Customers care about quality of service and being able to use their appliances any time needed. Therefore, any interruption in service is undesirable from the customer's perspective. The utility's perspective of reliability considers both the service reliability at the load points and reliability of the supply side which may include reliability of generation, transmission and distribution assets, as well [7].

There are many factors that affect and influence the smooth operation of an electric power distribution grid, which also impact on the reliability of electric power distribution grids. Typical of these factors are system configuration, interruption duration, weather conditions, failure rate and protection of equipment failure [8, 9].

According to Sekhar *et al*., (2016) and Harikrishna et *al*., (2013), historical assessment and predictive assessment are two key approaches of reliability evaluation in power distribution systems [10, 11]. Predicting distribution system reliability performance is normally concerned with the electric supply adequacy at the customer load point and the basic indices used in practice are load point average failure rate, average outage duration, and the average annual outage time [10]. In [11], Harikrishna *et al*. (2013) predicted future behaviour of industrial and urban feeders of a power distribution system using reliability indices. Bernstein *et al*., (2017) developed reliability prediction of devices exhibiting multiple failure mechanisms using multiple temperature operational life (MTOL) testing data to calculate failure in time (FIT) values [12]. Tang *et al*. (2014), predicted the remaining useful life of lithium ion batteries based on a Wiener process and the method was validated by numerical examples and a case study [13]. An energy consumption method for electric vehicles was predicted out of combining real-world measured driving data with geographical and weather data for energy efficient routing in [14]. Zhany *et al*. (2020) in their work, predicted reliability of future smart cities constructed with urban traffic systems and power distribution systems with regard to influence of commercial charging lots on them [15]. The expected energy not supplied cost (EENSC) and the expected travel time cost (ETTC) as novel unifying of both systems, reliability indices were formulated and used for the prediction. Wang and Tian (2018) proposed an adaptive reliability prediction method for a long-time running intelligent satellite power distribution system that operates

15 to 20 years in orbit using real-time lifetime data, real-time degradation data and the "before launching" ground testing data to construct an additive degradation model for the reliability prediction [16].

The reliability of power supply to customers in a whole metropolis has not been studied. In these days of rapid expansion where rural areas are metamorphosing into municipalities at an alarming rate due to population growth, it is more realistic to consider wider coverage areas of the dimension of a metropolis for reliability studies and prediction. This offers a better and more useful resolution with regard to planning, improvement and reliability of power supply in the midst of the rapid expansion witnessed of late. The contribution of this paper lies in prediction of reliability of power supply in the Sekondi-Takoradi metropolis of Ghana. This metropolis has so far not been subjected to any such study. The novelty of this paper is a study on reliability prediction of a network comprising over 332 buses and 434 circuit feeders. The rest of this paper is organised as follows: In Section 2 is presented the reliability indices, predictive reliability analysis, data collection and analysis and the predictive reliability assessment. Section 3 presents the results and discussions and conclusive remarks are given in Section 4.

2. Materials and Methods

2.1. Reliability Indices

Reliability indices are statistical aggregations of reliability data for a well-defined set of loads, components or customers. Most reliability indices are average values of a particular reliability characteristic for an entire electric power distribution system, operating region, substation, service territory, or feeder. Analytical and simulation techniques are usually used in electric power distribution grid reliability indices evaluation. The difference between these two techniques is in the way the input data are evaluated to obtain the reliability indices. Analytical techniques represent the system by simplified mathematical models derived from mathematical equations and evaluate the reliability indices using direct mathematical solutions. Simulation techniques on the other hand, estimate the reliability indices by simulating the actual process and the stochastic behaviour of system. Therefore, the simulation technique treats the problem as a series of real experiments conducted in simulated domain. It estimates probability of the events and other indices by counting the number of times an event occurs [17]. At the distribution level, electric power supply reliability is defined by two sets of indices namely, load point indices and the system performance indices.

2.1.1. Customer Load Point Indices

The primary reliability indices at the customer load point are: expected frequency of failures, λ, the average duration of failure, r and the average annual outage time (unavailability), U. They are evaluated for each load point for any meshed or parallel electric power distribution system. The load point indices measure the expected number of outages and their duration for individual customers [18]. Eq. (1) gives the generic formula for failure rate, whilst the system's failure rate, failure duration, and interruption time, are given by Eq. (2), Eq. (3) and Eq. (4) respectively [16, 19].

$$\lambda = \frac{\text{Number of Times Failure Occurred}}{\text{Number of Unit-hours of Operation}} \text{ (occ/year)} \qquad (1)$$

Assuming that there are *m* components in series:

$$\lambda_s = \sum_{i=1}^{m} \lambda_i \text{ (occ/year)} \qquad (2)$$

$$r_s = \frac{\sum_{i=1}^{m} \lambda_i r_i}{\lambda_s} \text{ (hours/failure)} \qquad (3)$$

$$U_s = \sum_{i=1}^{m} \lambda_i r_i \text{ (hours/year)} \qquad (4)$$

where, λ_s is system's failure rate, λ_i is failure rate of system's i^{th} component, r_s is system's failure duration, U_s is system interruption time, and $\sum$ is summation function.

2.1.2. System Performance Indices

Load point indices measure the expected number of outages and their duration for individual customers. System average interruption frequency index (SAIFI) and system average interruption duration index (SAIDI) measure the overall reliability of the electric power distribution system. The third popular index most utilities have been benchmarking is customer average interruption duration index (CAIDI). These indices can be used to compare the effects of various design and maintenance strategies on system reliability. A lot of different reliability indices have been proposed and are being used. They can be divided into four main categories:

1. Indices that measure the frequency of sustained interruptions.
2. Indices that measure the duration of sustained interruptions.
3. Indices that measure the frequency of momentary interruptions.
4. Indices that measure the frequency and depth of voltage sags.

The first two categories have been considered "reliability" issues, while the last two are regarded as "power quality" issues. The main reliability indices used for sustained interruptions (outages in excess of five minutes while excluding major event days) are the SAIFI, SAIDI and CAIDI [21, 22]. System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) can be determined by Eq. (5) and Eq. (6,) respectively using the customer load point indices as follows [20]:

$$SAIFI = \frac{(\lambda_1 a)+(\lambda_1+\lambda_2)b+\ldots\ldots\ldots\ldots(\lambda_1+\ldots\ldots\ldots\lambda_k)k}{a+b+\ldots\ldots\ldots\ldots\ldots+k} \qquad (5)$$

$$SAIDI = \frac{(u_1 a)+(u_2 b)..........(u_k)k}{a+b..................+k} \quad (6)$$

where, λ_1 is failure rate at load point 1, λ_2 is failure rate at load point 2, λ_k is failure rate at load point k, u_1 is interruption time at load point 1, u_2 is interruption time at load point 2, u_k is interruption time at load point k, a is number of customers at load point 1, b is number of customers at load point 2, and k is number of customers at load point k.

SAIFI is the average number of times that a customer experiences an outage during the year (or time period under study). The SAIFI is found by dividing the total number of customers interrupted by the total number of customers served. Analytically, SAIFI is given in Eq. (7).

$$SAIFI = \frac{Total\ Number\ of\ Customer\ Interruptions}{Total\ Number\ of\ Customers\ Served} = \frac{\sum N_i}{N_T} \quad (7)$$

where, SAIFI is system average interruption frequency index in interruptions/year/customer or interruptions/month/customer, N_i is total number of customers interrupted, and N_T is total number of customers served.

The index SAIDI measures the total duration of an interruption for the average customer during a given time period. SAIDI is normally calculated on either monthly or yearly basis; however, it can also be calculated daily, or for any other time period. Analytically, SAIDI is expressed by Eq. (8).

$$SAIDI = \frac{Sum\ of\ Customer\ Interruption\ Durations}{Total\ Number\ of\ Customers\ Served} = \frac{\sum (r_i * N_i)}{N_T} \quad (8)$$

where, SAIDI is system average interruption duration index in hours/year/customer or hours/year/customer, r_i is restoration time in minutes,

Once an outage occurs, the average time to restore service is found from the customer average interruption duration index (CAIDI) expressed in hours/year/customer or hours/month/customer. Analytically, CAIDI is expressed by Eq. (9).

$$CAIDI = \frac{Sum\ of\ Customer\ Interruption\ Durations}{Total\ Number\ of\ Customer\ Interruptions}$$

$$= \frac{\sum (r_i * N_i)}{\sum N_i} = \frac{SAIDI}{SAIFI} \quad (9)$$

CAIFI which is Customer Average Interruption Frequency Index measures the average number of interruptions per customer interrupted per year. It is simply the number of interruptions that occurred divided by the number of customers affected by the interruptions. Accordingly, CAIFI is expressed by Eq. (10).

$$CAIFI = \frac{Total\ Number\ of\ Interruptions}{Total\ Number\ of\ Customers\ Interrupted} = \frac{\Sigma(N_o)}{\Sigma(N_i)} \quad (10)$$

where, CAIFI is customer average interruption frequency index in inter./year/customer or inter./month/customer and N_o is total number of interruptions.

Average service availability index (ASAI), is the ratio of the total number of customer hours that service was available during a given time period to total customer hours demanded. The ASAI is usually calculated on either a monthly basis (730 hours) or a yearly basis (8760 hours), but can be calculated for any time period. ASAI is expressed by Eq. (11).

$$ASAI = \frac{Customer\ Hours\ of\ Available\ Service}{Customer\ Hours\ Demanded} = \left[1 - \left\{\frac{\Sigma(r_i * N_i)}{N_T * T}\right\}\right] * 100 \quad (11)$$

where, ASAI is average service availability index in per unit, T is time period under study in hours.

ASAI can also be computed using Equation (12) or Equation (13) on a yearly basis (8,760 hours) or on a monthly basis (730 hours).

$$ASAI = \frac{8760\ -\ SAIDI}{8760} \quad (12)$$

$$ASAI = \frac{730\ -\ SAIDI}{730} \quad (13)$$

2.2. Predictive Reliability Analysis

Historical assessment generally involves the collection and analysis of electric power distribution network outage and customer interruption data. Predictive assessment determines long term behaviour of an electric power distribution grid by combining component failure rates, and the duration of repair, restoration, switching and isolation activities for a given network configuration. The historical assessment procedure looks back at the past behaviour of the electric power distribution grid, whilst the predictive reliability (PR) looks forward at future system behaviour [1]. Analysis of PR normally helps in determining the performance state that the design, planning, and operation of the grid will achieve when certain reliability objectives and associated performance outcomes are met. Also, predictive reliability performance assessment helps predict the reliability performance of the system after any expansion and subsequently quantify the impact of adding new components to the system.

Electric power utility companies are faced with an aging infrastructure, increasing risk of blackouts and brownouts, costly unplanned maintenance issues, security threats to remote facilities, and rising costs. Utility companies are looking for ways to address these issues that will improve the reliability of electric power delivery while reducing costs [23]. The Electricity Company of Ghana (ECG) global annual operational performance indicators stated the following with regards to the company's operations [24]:

i. Annual fault rate reduction is 6%.
ii. Annual outage duration reduction is 10%.
iii. Annual customer growth is 9.8%.
iv. Number of affected customers per annum is 6%.

The PR of electric power distribution components is carried out using the stated performance indices. The PR is conducted by computing reliability indices using present fault rates, outage durations and number of affected customers. The following are defined for the analysis:

W = Reference outage frequency

X = Reference outage duration (hours)

Y = Reference total number of customers

Z = Reference number of affected customers

W_{20} = Predicted outage frequency for the year 2020

X_{20} = Predicted outage duration for the year 2020

Y_{20} = Predicted total number of customers for the year 2020

Z_{20} = Number of affected customers for the year 2020

W_{25} = Predicted outage frequency for the year 2025

X_{25} = Predicted outage duration for the year 2025

Y_{25} = Predicted total number of customers for the year 2025

Z_{25} = Number of affected customers for the year 2025

W_{30} = Predicted outage frequency for the year 2030

X_{30} = Predicted outage duration for the year 2030

Y_{30} = Predicted total number of customers for the year 2030

Z_{30} = Number of affected customers for the year 2030.

Using ECG performance indices, the following that is Eq. (13) to Eq. (16) are obtained for the year 2020:

$$W_{20} = W - 3*6\%W = W - 18\%W \quad (14)$$

$$X_{20} = X - 3*10\%X = X - 30\%X \quad (15)$$

$$Y_{20} = Y + 3*9.8\%Y = Y + 29.4\%Y \quad (16)$$

$$Z_{20} = Z - 3*10\%Z = Z - 30\%Z \quad (17)$$

where, three (3) is the year interval between the year 2017 and the year 2020.

For the year 2025, the PR is given by Equation (18) to Equation (21).

$$W_{25} = W_{20} - 5*6\%W_{20} = W_{20} - 30\%W_{20} \quad (18)$$

$$X_{25} = X_{20} - 5*10\%X_{20} = X_{20} - 50\%X_{20} \quad (19)$$

$$Y_{25} = Y_{20} + 5*9.8\%Y_{20} = Y_{20} + 49\%Y_{20} \quad (20)$$

$$Z_{25} = Z_{20} - 5*10\%Z_{20} = Z_{20} - 50\%Z_{20} \quad (21)$$

where, five (5) is the year interval between the year 2020 and the year 2025.

Also, for the year 2030, the PR is given by Equation (22) to Equation (25).

$$W_{30} = W_{25} - 5*6\%W_{25} = W_{25} - 30\%W_{25} \quad (22)$$

$$X_{30} = X_{25} - 5*10\%X_{25} = X_{25} - 50\%X_{25} \quad (23)$$

$$Y_{30} = Y_{25} + 5*9.8\%Y_{25} = Y_{25} + 49\%Y_{25} \quad (24)$$

$$Z_{30} = Z_{25} - 5*10\%Z_{25} = Z_{25} - 50\%Z_{25} \quad (25)$$

where, five (5) is the year interval between the year 2025 and the year 2030.

2.3. Data Collection and Analysis

2.3.1. Planned and Unplanned Outage Analysis

The data used for the electric power distribution grid reliability analysis and prediction for the Secondi-Takoradi metropolis were obtained from the regional office of Electricity Company of Ghana (ECG) in Takoradi as secondary data or reliable historical data. The metropolis is served by 33/11 kV lines from tree primary substations. ECG is in charge of operations and maintenance of all electric power distribution grids within the Western region which is one of the ten regions of Ghana. The project unit of the regional office of the company provided all the necessary outage data from the field for the years 2015, 2016 and 2017. The outage data indicates the date of occurrence, the affected feeders, total number of customers served at the time of the occurrence, the time of the outage, the time of the fault restoration, the duration of the outage, and the total number of customers affected by the outage. Table 1 gives the summary of the average number of customers of the metropolis affected by an outage. The summary of planned and unplanned outages and their frequencies and durations for 2015, 2016 and 2017 are presented in Table 2, Table 3 and Table 4, respectively.

Table 1. *Summary of average number of customers affected by an outage.*

Month of the Year	Average Number of Active Customers Served in the Metropolis		
	2015	2016	2017
January	127,920	132,500	156,341
February	127,920	132,500	156,341
March	127,920	132,500	156,341
April	127,920	132,500	156,341
May	127,920	132,500	156,341
June	127,920	132,500	156,341
July	127,920	132,500	156,341
August	127,920	132,500	156,341
September	127,920	132,500	156,341
October	127,920	132,500	156,341
November	127,920	132,500	156,341
December	127,920	132,500	156,341
Total	127,920	132,500	156,341

Table 2. *Summary of outage frequency and duration for the year 2015.*

Month of the year	Planned outages		Unplanned outages		Total outages	
	Freq./Month	Duration (Hours)	Frequency /Month	Duration (Hours)	Frequency /Month	Duration (Hours)
January	34	6.4	296	1,478.9	330	1,485.3
February	47	3.2	365	1,009.2	412	1,012.4
March	34	4.3	325	856.4	359	860.7
April	42	11.2	287	779.2	329	790.4
May	26	8.5	387	568.4	413	576.9
June	52	9.1	298	378.7	350	387.8
July	46	7.2	366	1,896.3	412	1,903.5
August	39	5.7	274	967.1	313	972.8
September	44	4.7	357	1124.7	401	1,129.4
October	29	6.1	396	1895.2	425	1,901.3
November	36	12.8	289	970.8	325	983.6
December	32	8.7	387	1785.5	419	1,794.2
Total	461	87.9	4,027	13,710.4	4,488	13,798.3

Table 3. *Summary of outage frequency and duration for the year 2016.*

Month of the Year	Planned Outages		Unplanned Outages		Total Outages	
	Freq./Month	Duration (Hours)	Frequency /Month	Duration (Hours)	Frequency /Month	Duration (Hours)
January	33	12.6	496	496.2	529	508.8
February	29	10.7	478	387.4	507	398.1
March	31	9.5	397	265.4	428	274.9
April	27	8.9	287	355.4	314	364.3
May	30	9.1	388	408.7	418	417.8
June	28	12.4	401	289.3	429	301.7
July	25	11.7	295	335.4	320	347.1
August	31	7.8	308	308.7	339	316.5
September	33	7.4	347	256.7	380	264.1
October	32	8.3	255	311.4	287	319.7
November	24	6.9	410	424.1	434	431
December	23	4.2	207	306.2	230	310.4
Total	346	109.5	4269	4,144.9	4,615	4,254.4

Table 4. *Summary of outage frequency and duration for the year 2017.*

Month of the Year	Planned Outages		Unplanned Outages		Total Outages	
	Freq./Month	Duration (Hours)	Frequency /Month	Duration (Hours)	Frequency /Month	Duration (Hours)
January	27	11.8	446	446.2	473	458.1
February	24	10.9	402	287.9	426	298.8
March	33	7.5	387	275.2	420	282.7
April	28	8.2	288	255.7	316	263.9
May	25	8.8	378	368.7	403	377.5
June	28	11.6	411	259.8	439	271.4
July	26	13.2	306	377.4	332	390.6
August	31	7.7	324	318.6	355	326.3
September	22	9.4	354	226.4	376	235.8
October	20	8.5	355	296.4	375	304.9
November	24	7.6	385	322.5	409	330.1
December	23	5.5	287	361.2	310	366.7
Total	311	110.7	4,323	3,796.1	4,634	3,906.8

2.3.2. The Distribution Grid Reliability Assessment

The historical outage data for the years 2015, 2016 and 2017 were used to determine historical reliability indices. The outage frequency, outage duration, hours for which service was demanded, total number of customers and number of affected customers were the actual information picked out of the historical outage data. The indices SAIFI, SAIDI, CAIDI, CAIFI, and ASAI were computed for each month of the years 2015, 2016 and 2017 and are presented in Table 5, Table 6 and Table 7, respectively.

Table 5. *Computed reliability indices for the year 2015.*

Month	Outage Freq./Month	Outage Duration (Hours)	Hours (for which Service is Demanded)	Total Number of Customers	Number of Affected Customers
January	330	1,485.3	744	127,920	6547
February	412	1,012.4	672	127,920	14,896
March	359	860.7	744	127,920	24,589

Month	Outage Freq./Month	Outage Duration (Hours)	Hours (for which Service is Demanded)	Total Number of Customers	Number of Affected Customers
April	329	790.4	720	127,920	32,874
May	413	576.9	744	127,920	47,856
June	350	387.8	720	127,920	17,896
July	412	1,903.5	744	127,920	22,589
August	313	972.8	744	127,920	12,637
September	401	1,129.4	720	127,920	29,632
October	425	1,901.3	744	127,920	16,235
November	325	983.6	720	127,920	5,489
December	419	1,794.2	744	127,920	7,008
Total	4,488	13,798.3	8,760	127,920	238,248

Table 5. *Continued.*

Month	SAIFI (Inter. /Cust.)	SAIDI (hours./Cust.)	CAIDI (Hrs./Cust.)	CAIFI (Inter./Cust.)	ASAI (p.u.)
January	0.00258	0.01161	4.50	0.05040	-0.99637
February	0.00322	0.00791	2.46	0.02766	-0.50655
March	0.00281	0.00673	2.40	0.01460	-0.15685
April	0.00257	0.00618	2.40	0.01001	-0.09778
May	0.00323	0.00451	1.40	0.00863	0.22460
June	0.00274	0.00303	1.11	0.01956	0.46139
July	0.00322	0.01488	4.62	0.01824	-1.55847
August	0.00245	0.00760	3.11	0.02477	-0.30753
September	0.00313	0.00883	2.82	0.01353	-0.56861
October	0.00332	0.01486	4.47	0.02618	-1.55551
November	0.00254	0.00769	3.03	0.05921	-0.36611
December	0.00328	0.01403	4.28	0.05979	-1.41156
Total	0.03508	0.10787	3.07	0.01884	-0.57515

Table 6. *Computed reliability indices for the year 2016.*

Month	Outage Freq./Month	Outage Duration (Hours)	Hours (for which Service is Demanded)	Total Number of Customers	Number of Affected Customers
January	529	508.8	744	132,500	8547
February	507	398.1	696	132,500	14,896
March	428	274.9	744	132,500	24,589
April	314	364.3	720	132,500	7,876
May	418	417.8	744	132,500	31,856
June	429	301.7	720	132,500	14,896
July	320	347.1	744	132,500	32,549
August	339	316.5	744	132,500	10,639
September	380	264.1	720	132,500	29,667
October	287	319.7	744	132,500	14,277
November	434	431	720	132,500	14,895
December	230	310.4	744	132,500	11,004
Total	4615	4,254.4	8,784	132,500	215,691

Table 6. *Continued.*

Month	SAIFI (Inter. /Cust.)	SAIDI (hours./Cust.)	CAIDI (Hrs./Cust.)	CAIFI (Inter./Cust.)	ASAI (p.u.)
January	0.00399	0.00384	0.96	0.06189	0.31613
February	0.00383	0.00300	0.79	0.03404	0.42802
March	0.00323	0.00207	0.64	0.01741	0.63051
April	0.00237	0.00275	1.16	0.03987	0.49403
May	0.00315	0.00315	1.00	0.01312	0.43844
June	0.00324	0.00228	0.70	0.02880	0.58097
July	0.00242	0.00262	1.08	0.00983	0.53347
August	0.00256	0.00239	0.93	0.03186	0.57460
September	0.00287	0.00199	0.70	0.01281	0.63319
October	0.00217	0.00241	1.11	0.02010	0.57030
November	0.00328	0.00325	0.99	0.02914	0.40139
December	0.00174	0.00234	1.35	0.02090	0.58280
Total	0.03483	0.03211	0.92	0.02140	0.51566

Table 7. *Computed reliability indices for the year 2017.*

Month	Outage Freq./Month	Outage Duration (Hours)	Hours (for which Service is Demanded)	Total Number of Customers	Number of Affected Customers
January	473	458.1	744	156,341	31,545
February	426	298.8	672	156,341	13,866
March	420	282.7	744	156,341	34,547
April	316	263.9	720	156,341	17,854
May	403	377.5	744	156,341	22,967
June	439	271.4	720	156,341	18,452
July	332	390.6	744	156,341	29,534
August	355	326.3	744	156,341	15,637
September	376	235.8	720	156,341	27,993
October	375	304.9	744	156,341	16,742
November	409	330.1	720	156,341	20,964
December	310	366.7	744	156,341	13,458
Total	4,634	3,906.8	8,760	156,341	263,559

Table 7. *Continued.*

Month	SAIFI (Inter. /Cust.)	SAIDI (hours./Cust.)	CAIDI (Hrs./Cust.)	CAIFI (Inter./Cust.)	ASAI (p.u.)
January	0.00303	0.00293	0.97	0.01499	0.38427
February	0.00272	0.00191	0.70	0.03072	0.55536
March	0.00269	0.00181	0.67	0.01216	0.62003
April	0.00202	0.00169	0.84	0.01770	0.63347
May	0.00258	0.00241	0.94	0.01755	0.49261
June	0.00281	0.00174	0.62	0.02379	0.62306
July	0.00212	0.00250	1.18	0.01124	0.47500
August	0.00227	0.00209	0.92	0.02270	0.56142
September	0.00240	0.00151	0.63	0.01343	0.67250
October	0.00240	0.00195	0.81	0.02240	0.59019
November	0.00262	0.00211	0.81	0.01951	0.54153
December	0.00198	0.00235	1.18	0.02303	0.50712
Total	0.02964	0.02499	0.84	0.01758	0.55402

2.4. Predictive Reliability Assessment Using Operational Performance Indices

The prediction of reliability indices of the electric power distribution grid for the years 2020, 2025 and 2030 was done using the average values of the years 2016 and 2017 data as the reference. The projected data for the predictions were obtained using Equation (13) to Equation (24). The above projected estimates were based on ECG's global annual performance indicators assuming that conditions would remain same. In determining the future reliability of the electric power distribution network, the failure rates of the various components were factored into the analysis. The failure rate, failure duration and interruption time were computed for all electric power distribution components that experienced an outage within the month for the year under review before summing them up to obtain the failure rate, failure duration and interruption time for that particular month. Components considered were: Overhead conductor (O/H), Underground cable (U/G), Circuit breaker (CB), Load isolator (LI), High tension fuse (HTF), Transformer (TF), Surge diverter (SD) and Protection system (PS). These components were assumed to be connected in series within the electric power distribution network. The electric power distribution grid was modelled and simulated using fifty (50) buses out of which forty (40) are load buses. Assuming an equal number of customers at each load point, the predicted number of customers is divided by the number of buses to obtain the number of customers at each load point for a particular year under review which is then used to determine SAIFI and SAIDI based on Equation (5) and Equation (6). The predictive reliability indices for the year 2020 were computed using Equation 1 through to Equation 6.

3. Results and Discussions

Predictive reliability indices for 2020, 2025 and 2030 are as given in Table 8, Table 9 and Table 10, respectively.

Table 8. *Predictive Reliability Analysis for the Year 2020.*

Month	λ (Freq./Month)	Average Duration of Failure, r (Hours)	Average Annual Outage Time, U (Hours/Month)	Outage Frequency	Total Number of Customers	Number of Affected Customers
January	0.0223	5.42	0.1209	411	186,881	6,014
February	0.0321	11.2	0.3595	383	186,881	4,314
March	0.0115	4.10	0.0472	348	186,881	8,870
April	0.0233	14.6	0.3402	258	186,881	3,860
May	0.0431	6.7	0.2888	337	186,881	8,223

Month	λ (Freq./Month)	Average Duration of Failure, r (Hours)	Average Annual Outage Time, U (Hours/Month)	Outage Frequency	Total Number of Customers	Number of Affected Customers
June	0.0532	8.2	0.4362	356	186,881	5,002
July	0.0212	9.4	0.1993	267	186,881	9,312
August	0.0321	5.6	0.1798	285	186,881	3,941
September	0.0411	7.2	0.2959	310	186,881	8,649
October	0.01521	8.9	0.1354	271	186,881	4,653
November	0.0214	9.2	0.1969	346	186,881	5,379
December	0.0131	10.8	0.1415	221	186,881	3,669
Total	0.3296	101.32	2.74	3,792	186,881	71,888

Table 8. *Continued.*

Month	SAIFI (Inter. /Cust.)	SAIDI (hours. /Cust.)	CAIDI (Hrs. /Cust.)	CAIFI (Inter. /Cust.)	ASAI (p.u.)
January	0.0014	0.0344	24.57	0.0683	0.99995
February	0.0020	0.1380	69.00	0.0888	0.99980
March	0.0007	0.0124	17.71	0.0392	0.99998
April	0.0015	0.1272	84.80	0.0668	0.99982
May	0.0027	0.1008	37.33	0.0410	0.99986
June	0.0034	0.1864	54.82	0.0712	0.99974
July	0.0013	0.0621	47.77	0.0287	0.99992
August	0.0020	0.0547	27.35	0.0723	0.99993
September	0.0026	0.1043	40.12	0.0358	0.99986
October	0.0010	0.0391	39.10	0.0582	0.99995
November	0.0013	0.0612	47.08	0.0643	0.99992
December	0.0008	0.0412	51.50	0.0602	0.99994
Total	0.0208	0.9618	46.24	0.0528	0.99989

Table 9. *Predictive Reliability Analysis for the Year 2025.*

Month	λ (Freq./Month)	Average Duration of Failure, r (Hours)	Average Annual Outage Time, U (Hours/Month)	Outage Frequency	Total Number of Customers	Number of Affected Customers
January	0.0196	2.71	0.0531	288	278,453	3,007
February	0.0279	5.60	0.1562	268	278,453	2,157
March	0.0105	2.05	0.0215	244	278,453	4,435
April	0.0210	7.30	0.1533	181	278,453	1,930
May	0.0388	3.35	0.1300	236	278,453	4,112
June	0.0372	4.10	0.1525	249	278,453	2,501
July	0.0170	4.70	0.0799	187	278,453	4,656
August	0.0276	2.80	0.0773	200	278,453	1,971
September	0.0325	3.60	0.1170	217	278,453	4,325
October	0.0128	4.45	0.0570	190	278,453	2,327
November	0.0188	4.60	0.0865	242	278,453	2,690
December	0.0121	5.40	0.0653	155	278,453	1,835
Total	0.2757	50.66	1.15	2,655	278,453	35,943

Table 9. *Continued.*

Month	SAIFI (Inter. /Cust.)	SAIDI (hours. /Cust.)	CAIDI (Hrs. /Cust.)	CAIFI (Inter. /Cust.)	ASAI (p.u.)
January	0.0012	0.0140	11.39	0.0958	0.99998
February	0.0018	0.0463	26.34	0.1242	0.99993
March	0.0007	0.0055	8.35	0.0550	0.99999
April	0.0013	0.0452	34.29	0.0938	0.99994
May	0.0024	0.0373	15.25	0.0574	0.99995
June	0.0023	0.0450	19.16	0.0996	0.99994
July	0.0011	0.0217	20.34	0.0402	0.99997
August	0.0017	0.0209	12.06	0.1015	0.99997
September	0.0020	0.0331	16.17	0.0502	0.99995
October	0.0008	0.0151	18.83	0.0817	0.99998
November	0.0012	0.0237	20.05	0.0900	0.99997
December	0.0008	0.0175	23.02	0.0845	0.99998
Total	0.0174	0.3253	18.7	0.0739	0.99807

Table 10. *Predictive Reliability Analysis for the Year 2030.*

Month	Λ (Freq./Month)	Average Duration of Failure, r (Hours)	Average Annual Outage Time, U (Hours/Month)	Outage Frequency	Total Number of Customers	Number of Affected Customers
January	0.0029	1.355	0.0531	202	414,895	1504
February	0.0064	2.8	0.1562	188	414,895	1079
March	0.0023	1.025	0.0215	171	414,895	2218
April	0.0023	3.65	0.1533	127	414,895	965
May	0.0043	1.675	0.1300	165	414,895	2056
June	0.0048	2.05	0.1525	174	414,895	1251
July	0.0036	2.35	0.0799	131	414,895	2328
August	0.0083	1.4	0.0773	140	414,895	986
September	0.0055	1.8	0.1170	152	414,895	2163
October	0.0024	2.225	0.0570	133	414,895	1164
November	0.0021	2.3	0.0865	169	414,895	1345
December	0.0015	2.7	0.0653	109	414,895	918
Total	0.0465	25.33	1.15	1860	414,895	17973

Table 10. *Continued.*

Month	SAIFI (Inter. /Cust.)	SAIDI (hours. /Cust.)	CAIDI (Hrs. /Cust.)	CAIFI (Inter. /Cust.)	ASAI (p.u.)
January	0.0010	0.0131	13.1000	0.1343	0.99997
February	0.0014	0.0424	30.2857	0.1742	0.99994
March	0.0101	0.0048	0.4752	0.0771	0.99998
April	0.0301	0.0423	1.4053	0.1316	0.99994
May	0.0013	0.0341	26.2308	0.0803	0.99995
June	0.0025	0.0416	16.6400	0.1391	0.99994
July	0.0102	0.0211	2.0686	0.0563	0.99997
August	0.0015	0.0204	13.6000	0.1420	0.99997
September	0.0103	0.0322	3.1262	0.0703	0.99996
October	0.0302	0.0132	0.4371	0.1143	0.99998
November	0.0601	0.0215	0.3577	0.1257	0.99997
December	0.0401	0.0154	0.3840	0.1187	0.99996
Total	0.1988	0.3021	1.5196	0.1035	0.99959

From Tables 8, 9 and 10, monthly-predicted values of SAIFI lie in the range 0.0007 to 0.0601, those of SAIDI are from 0.0048 to 0.1864, those of CAIDI are from 0.3577 to 84.80, for CAIFI are from 0.0287 to 0.1742 and ASAI is from 0.99974 to 0.99999. The monthly ASAI values in particular look promising even though some could not meet the IEEE standard 1366-2003 requirement of 0.99982.

Figures 1 to 5 show the predictions for the three years namely, 2020, 2025 and 2030 under consideration.

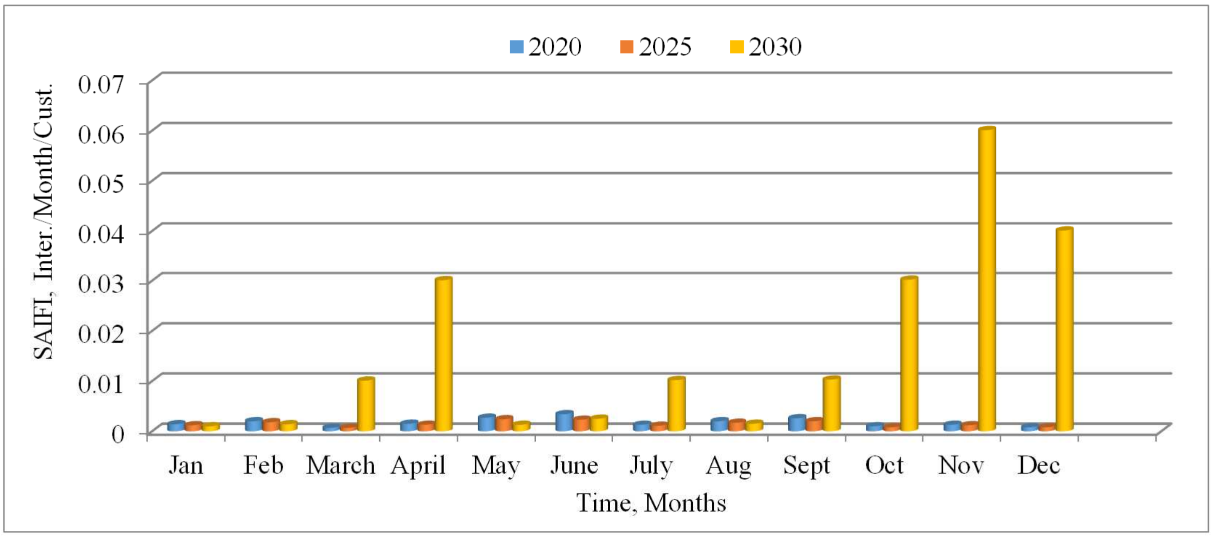

Figure 1. *Monthly Predicted SAIFI.*

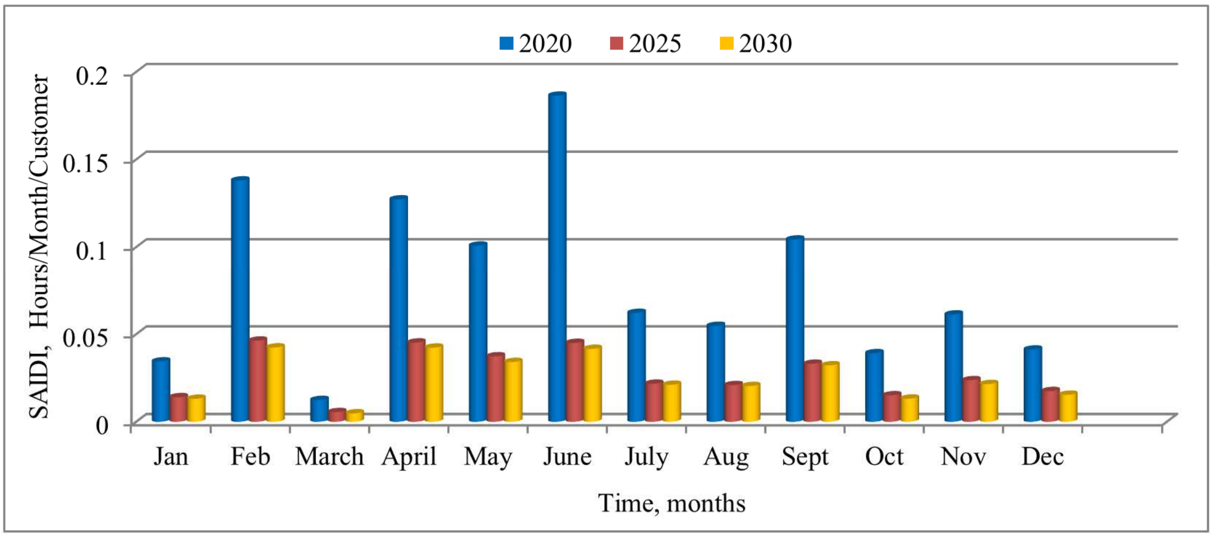

Figure 2. *Monthly Predicted SAIDI.*

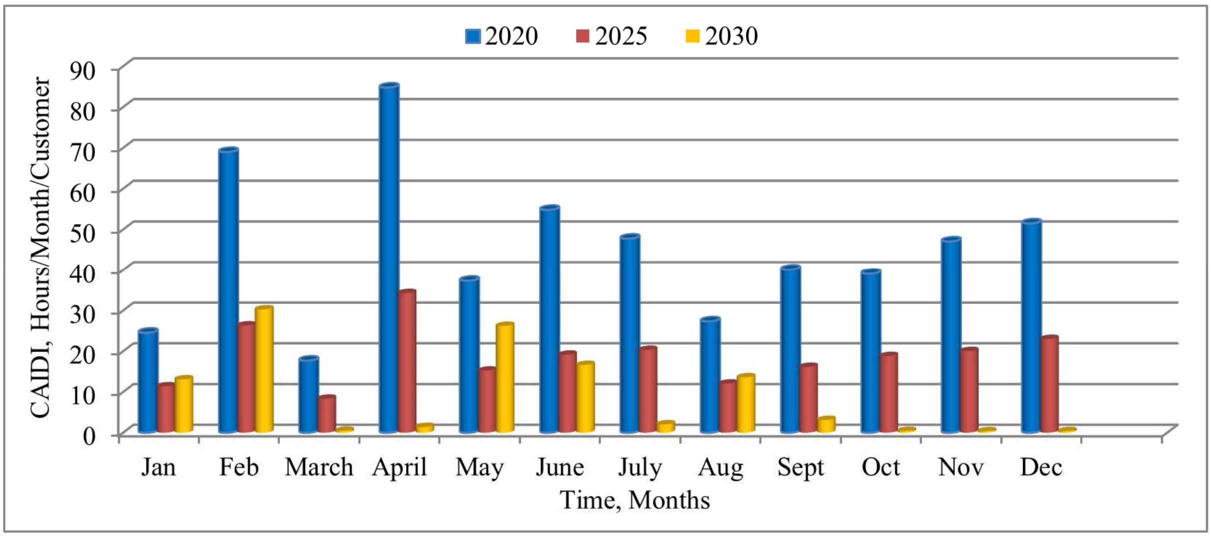

Figure 3. *Monthly Predicted CAIDI.*

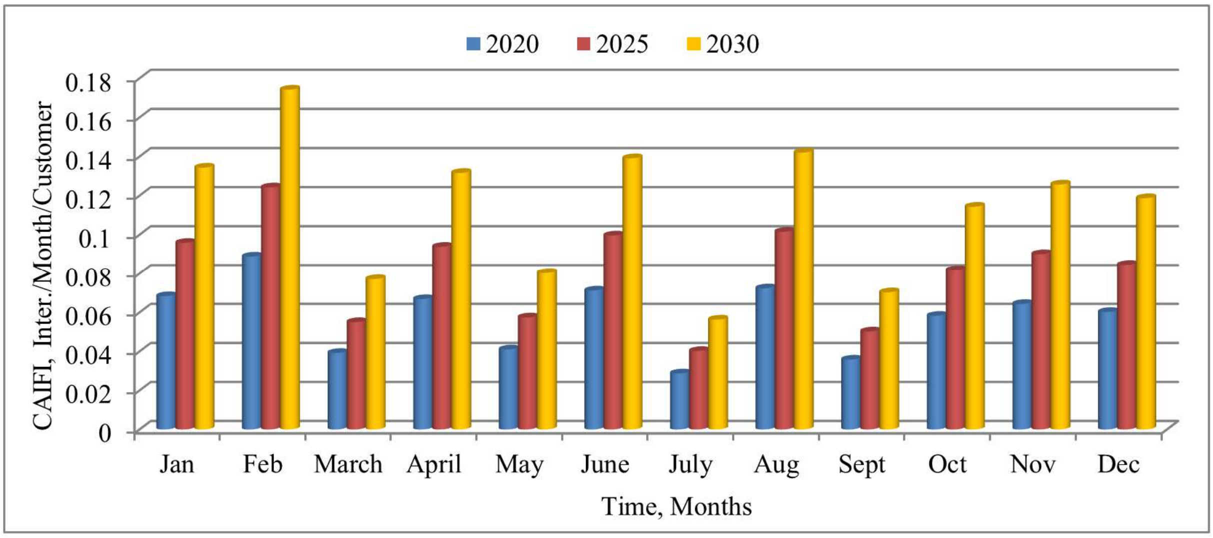

Figure 4. *Monthly Predicted CAIFI.*

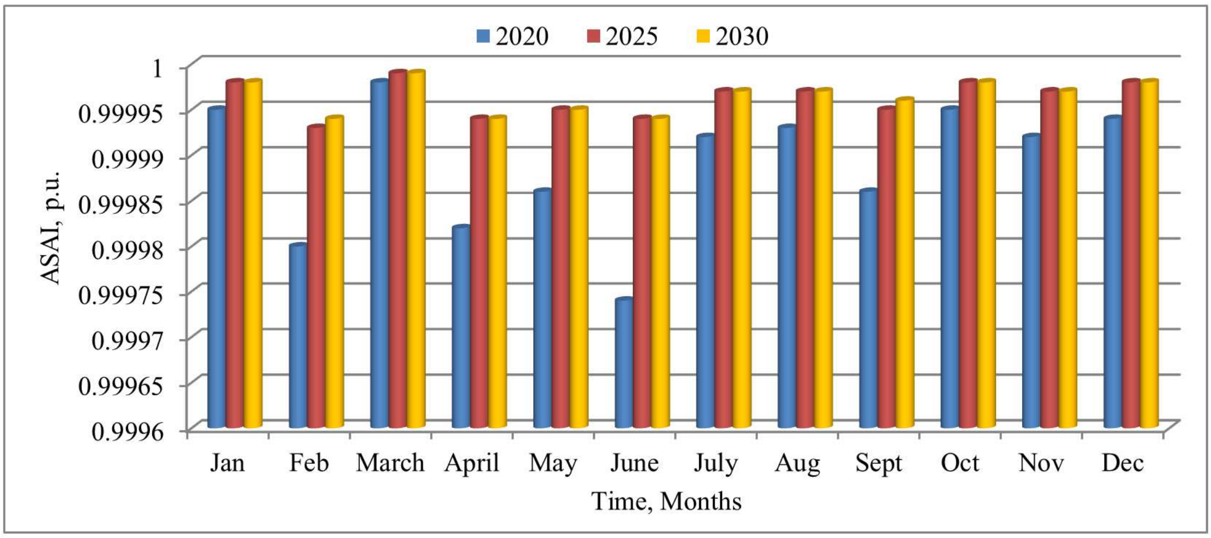

Figure 5. *Monthly Predicted ASAI.*

From Figure 1, the best predicted monthly SAIFI value of 0.0007 interruptions per customer per month would be obtained in the years 2025 and 2030 in the month of March. The worst SAIFI value of 0.0601 interruptions per customer per month would be attained in the month of November in the year 2030. The predicted monthly SAIFI values for the years 2020, 2025 and 2030 are in tune with the IEEE standard 1366 –2003 requirement of 0.92 interruptions per customer per month [25]. The best SAIDI value of 0.0048 hours or 0.29 minutes per customer per month would be attained in the month of March in the year 2030 as indicated by Figure 2. This could be attributable to the projected reduction in electric power distribution network outage time in the year 2030. The worst SAIDI value of 0.1864 hours or 11.2 minutes per customer per month would be attained in the month of June in 2020. The interesting thing about the predicted SAIDI values for the years 2020, 2025 and 2030 is that they are all in tune with the IEEE standard 1366–2003 requirement of 7.5 minutes outage duration per customer per month [25]. From Figure 3, the average customer within the metropolis would experience the shortest interruption in outage lasting for 0.3577 hours or 21.5 minutes in the month of November in the year 2030. The longest outage duration lasting for 84.8 hours would be experienced by the customers in the month of April in the year 2020. This could be due to the fact that restoring electric power distribution components back into service might take much longer time especially outages involving underground cable faults. This is in variance with IEEE standard 1366–2003 requirement of 6.3 minutes outage duration per customer per month [25].

The best predicted CAIFI value of 0.0287 would be achieved in the year 2020 in the month of July as given by Figure 4. The worst predicted CAIFI value of 0.1742 would be recorded in the month of February in the year 2030. The predicted CAIFI values for the rest of the months for the years 2020, 2025 and 2030 showed upward trend. This trend would be as a result of projected reduction in the number of customer interruptions and the number of affected customers. From Figure 5, the monthly predicted ASAI values are all encouraging. This encouraging trend is observed for the years 2020, 2025 and 2030. This could be as a result of the low number of predicted number of interruptions for the months of the years 2020, 2025 and 2030. Some of the monthly predicted ASAI values are within the range of 0.99999. This gives an indication that service would be available in those months as much as demanded by the customers. The predicted monthly ASAI values for the years 2020, 2025 and 2030 are all better than the IEEE standard 1366–2003 requirement of 0.99982 service availability per customer per month [25].

4. Conclusion

The monthly unplanned outages and total outage frequencies and their durations keep on fluctuating but showed slight decrement on yearly basis for the years 2015, 2016 and 2017. The predicted SAIFI, SAIDI, CAIDI and ASAI values of the years 2020, 2025, and 2030 gave an indication that reliability of the electric power distribution grid within the metropolis would see varying monthly but improved yearly performances. Better performances regarding these indices are envisaged as the years advance towards the year 2030. CAIFI offers generally progressive performance for the months as the years' advance to 2030. The predicted reliability indices can only be achieved if the underlying global operational performance indices used in their predictions remain same or the operating conditions and issues of component availability improve for the better as the years advance. Outcome of this research will help in planning and improving the network, as well as facilitate reliable supply of power to customers in the near future. As an extension to this research, we shall look at component availability of the network in our future research endeavours.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Chowdhury, A. A., Koval, D. O. (2009). Power distribution system reliability, practical methods and applications. John Wiley & Sons, Inc., Hoboken, New Jersey, USA.

[2] Cepin, M. (2011). Assessment of power system reliability, methods and applications. Springer, London, UK.

[3] Brown, R. E. (2009). Electric power distribution reliability. 2nd Edition, CRC Press, Taylor & Francis Group, NW, USA.

[4] Gonen, T. (2008). Electric power distribution system reliability engineering. 2nd edition, CRC Press, Taylor & Francis Group, NW, USA, pp. 1-45.

[5] Vrana, T. K., Johansson, E. (2011). Overview of power system reliability assessment techniques. http://www.cigre.org, accessed on Dec. 30, 2013.

[6] Kazemi, S. (2011). Reliability evaluation of smart distri-bution grids. Doctoral dissertation, Aalto University, Greater Helsinki, Finland.

[7] Kahrobaee, S. (2014). Reliability modelling and evaluation of distributed energy resources and smart power distribution systems. PhD dissertation, University of Nebraska, Lincoln, Canada.

[8] Lamour, B. G. (2011). An analysis of the reliability of the 22 kV distribution network of Nelson Mandela Bay Municipality. Research Dissertation, Magister Technologiae, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa.

[9] Dorji, T. (2009). Reliability assessment of distribution systems - Including a case study on Wangdue distribution system in Bhutan. MSc Thesis, Norwegian University of Science Technology, Trondheim, Norway.

[10] Sekhar, P. C., Deshpande, R. A., Sankar, V. (2016). Evaluation and improvement of reliability indices of electrical power distribution system. Proceedings of the 2016 IEEE National Power Systems Conference, Bhubaneswar, India.

[11] Harikrishna, K. V., Ashok, V., Sekhar, P. C., Raghunatha, T., Deshpande, R. A. (2013). Predictive reliability assessment in the power distribution system. The Journal of CPRI, 9 (3): 33-42.

[12] Bernstein, J. B., Bensoussan, A., Bender, E. (2017). Reliability prediction with multiple temperature operational life (MTOL). Microelectronics Reliability, 68: 91–97.

[13] Tang, S., Yu, C., Wang, X., Guo, X., Si, X. (2014). Remaining useful life prediction of lithium-ion batteries based on the Wiener process with measurement error. Energies, 7: 520–547, https://doi:10.3390/en7020520.

[14] De Cauwer, C., Verbeke, W., Coosemans, T., Faid, S., Van Mierlo, J. (2017). A data-driven method for energy consumption prediction and energy-efficient routing of electric vehicles in real-world conditions. Energies, 10 (608): 1–18, https://doi:10.3390/en10050608.

[15] Zhany, C., Zhao, X., Shahidehpour, M., Li, W., Wen, L., Yang, Z. (2020). Reliability assessment of coordinated urban transportation and power distribution systems considering the impact of charging lots. IEEE Access, 8: 30536–30547. https://doi:10.1109/ACCESS.2020. 2973035.

[16] Wang, J., Tian, Y. (2018). An adaptive reliability prediction method for the intelligent satellite power distribution system. IEEE Access, 6: 58719–58727. https://doi:10.1109/ACCESS.2018.2875117.

[17] Supriya, M. D., Chandra, S. R. A., Mohan, K. R., Vasanth Kumara, T. M. (2014). Distribution system reliability evaluation using time sequential Monte Carlo simulation. ITSI Transactions on Electrical and Electronics Engineering, Bangalore, India, 2 (1): 24-30.

[18] Izuegbunam, F. I., Uba, I. S., Akwukwaegbu, I. O., Dike, D. O. (2014). Reliability evaluation of Onitsha power distribution network via analytical technique and the impact of PV systems. IOSR Journal of Electrical and Electronics Engineering, 9 (3): 15-22.

[19] Onime, F., Adegboyega, G. A. (2014). Reliability analysis of power distribution system in Nigeria: A case study of Ekpoma network, Edo State. International Journal of Electronics and Electrical Engineering, 2 (3): 175-182.

[20] Anthony, R. (2014). Reliability analysis of distribution network, MSc Thesis, Tun Hussein Onn University of Malaysia, Malaysia.

[21] Anon. (2012). Reliability improvements from the application of distribution automation technologies initial results. http://www.smartgrid.gov/files/Distri-bution Reliability Report - Final.pdf. pp. 2-11, accessed on Jun. 18, 2015.

[22] Islam, A. (2009). Smart grid reliability assessment under variable weather conditions. PhD dissertation, University of South Florida, South Florida, USA.

[23] Anon. (2016). System reliability and availability. http://www.EventHelix.com, accessed on Jun. 12, 2016.

[24] Anon. (2013). Proposal for review in distribution service charge. http://www.scribd.com/document/251913878/Tariff-Proposal-for-2013-ECG, accessed on Jul. 22, 2015.

[25] Glover, J. D., Sarma, M. S., Overbye, T. J. (2012). Power system analysis and design, 5th Edition, Global Engineering Publishers, U.S.A.