Reliability Assessment of an Off-Grid Hybrid Micro-Grid Power System (HMPS) for a Remote Community in Nigeria

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ABSTRACT. Power System reliability assessment is one of the most crucial mensurations to evaluate power provider services and continuous availability. Hybrid Renewable Energy Systems (HRES) are an effective means to provide off-grid electrification to the rural areas that predominantly do not have access to electricity. This paper presents the reliability performance of a typical remote Obayantor community hybrid micro-grid in Edo state, Southern Nigeria. The hybrid energy system provides power for 90 households via a combination of 300W Solar Photovoltaic (PV) Modules, 1200Ah back-up battery system, and a 65kW diesel generator. The PV modules generate power throughout the day; the back-up provides energy source in the night while the diesel generator is sparingly used only in the event of faults, maintenance, or repairs. The reliability indices calculated were Mean Time to Repair (MTTR), Mean Time Between Failure (MTBF), and Availability using the outage data obtained from the micro-grid between 2015 and 2019. The results recorded showed that the micro-grid was always available due to low downtime and low frequency of outages over the five years studied. Except in 2018, when the result recorded had the highest rate of power of interruption, which gave rise to the smallest value of availability and MTBF obtained in the same year. 2015 and 2019 had the highest availability value of 99.8%, and this value showed a similar trend to MTBF with the highest value in 2015 and the minimum value in 2018.

Keywords: Micro-grid, Reliability, Availability, power system, Solar PV

1. Introduction

A reliable electric power supply is an essential requirement for the economic development and modernization of any nation. The lack of electricity can intensify poverty, especially in developing countries[1]. Research has shown that 1.3 -1.6 billion people in the world living in isolated locations do not have access to power supply[2][3]. With the high rate of development of the world’s economy, power demand is rising dramatically, and the continuous dependence on fossil sources is having adverse effects on the earth’s ecosystem through atmospheric pollution and global warming. Hence, the need for drastic diversification into renewable energy sources to maintain a safer atmosphere and invariably eradicate energy catastrophes and environmental problems that are continually causing the
emission of greenhouse gases[4][5][6][7][8][9] The environmental-friendly renewable energy sources are gradually occupying a larger share of the energy market previously dominated by the conventional fossil-based power plants[10][11]. The reliability of renewable power sources alone involves a high degree of uncertainty of power supply and the variability of energy sources caused by stochastic weather conditions.

Reliability assessment is a crucial tool used to analyze the performance and feasibility of a micro- grid. Reliability is a means of providing power services to customers continuously with less or no interruptions [12]. Storage systems are added to HRE To improve the reliability indices of a microgrid and ensure a reduction in the loss of load probability[13]. Reliability studies are thus very crucial to utility companies primarily in the areas of the distributed energy system (DES) such as micro-grid[2-4] [14].

There has been a vast number of reliability studies of a renewable energy system in literature, but a few will be considered here as related to this research. Ghaedi et al. studied the effects of weather on the availability of a hybrid energy system [15]. Noor et al. analyzed the reliability of a small-scale DC micro-grid using the stochastic hybrid system for transportation electrification systems[16]. They considered system components failure rate only without considering other reliability indices.

The author in [17], studied the reliability evaluation from the demand and supply point of view for a stand-alone micro-grid. Iqbal and Shahzad carried out the reliability analysis of a campus microgrid by considering only carbon emission and analysis of cost energy resources availability [18]. Kekezoglu et al. evaluated reliability indices such as Availability, Loss of Energy Expectation (LOEE), and Loss of Load Expectation (LOLE) by considering Davutpasa University Campus[19].

A stand-alone micro-grid with consideration for generation and load using Monte Carlo simulation evaluated Loss of Load Expectation (LOLE) and Loss of Load Factor (LOLF) indices [20]. Also, in [5], a Monte-Carlo simulation was used to evaluate the reliability of multiple micro-grids of a distribution power network. The studies revealed that the overall system reliability would increase with the inclusion of distributed generations and storage. The authors in [6-7] examined an islanded mode of micro-grid reliability based on both component repair and historical data using Monte-Carlo simulation, evaluating discretized renewable energy system output, and the probability for each step.

1.1 Micro-grid

The micro-grid is an integration of various distributed energy sources including, renewable energy and non-renewable resources. Usually operated in an islanded mode, grid-connected mode, or off-grid (isolated) mode. They could come with features that are attractively flexible in terms of distributed generation[21]. The diversity of various energy sources enhances microgrid network reliability[22][23][24]. While the addition of Backup Storage Systems (BSS) and diesel generators solves, the challenges of intermittency often associated with such networks [2][24.] The diesel generators are commonly used as an alternative source when both the Solar PV and the Storage system are not available [1, 2].
2. Materials and Methods

Several authors have presented methods to assess the reliability of Micro-grid, especially at customer load points and also as a whole. These methods include classified as analytical (systematic) methods, simulation methods, and hybrid methods. However, in this paper, a systematic approach was considered. Historical data were collected from the Microgrid Maintenance Operators for a period of 5 years starting from 2015 to 2019, as shown in table 1.

2.1 Site assessment of study area and data collection

Nigeria lies within the tropical zone but usually experiences a prolonged rainy season and short dry season. The Obayantor community in Benin City, Southern part of Nigeria, is situated in Ikpoba-Okha local government of Edo state, with an approximate area of 862 km$^2$. The remote community power consumption is not as high as the urban area. The use is mainly for lighting, electric fans, and essential domestic appliances such as refrigerators, water heater, and freezers.

The micro-grid started power generations in May 2015 consisting of 300W solar PV modules, a 65kW diesel generator, an MPPT charge controller, a bi-directional converter system, and a battery storage system. The surveyed area has zero grid electricity connection. The Obayantor community lies geographically within latitude 6°26 and 6°34 North of the Equator, longitude 5°35 and 5.60° East of the Greenwich Meridian. The location temperature is about 26.2°C with an annual average solar radiation of 4.35kWh/m$^2$/day, and it has an elevation of 88 meters above sea level. The aerial view of the Obayantor community is as shown in Figure 1, while Figure 2 presents the micro-grid structure.

![Fig. 1: Obayantor community as seen from Aerial view](image-url)
2.2 Reliability and availability assessment of Obayantor Micro-grid

Five years of data were collected and used for the reliability and availability analysis of the Obayantor micro-grid, evaluating the metrics: Mean-Time-To-Repair (MTTR) and Mean-Time-Between Failures (MTBF), which is related to the duration of outages [26].

2.2.1 Mean-Time-To-Repair (MTTR)

MTTR is the expected overall time it takes to carry out preventative maintenance or corrective repairs divided by the total number of Outages [1]

\[
MTTR = \tau = \frac{1}{\mu} = \frac{\text{Total Downtime of the system}}{\text{Number of outages}}
\] (1)

\[
\mu = \frac{1}{\tau}
\] (2)
2.2.2 \textbf{Mean-Time Between Failures (MTBF)}

MTBF is the time passed before a power network break down under constant failure rate,

\[
MTBF = \frac{1}{\lambda} = \frac{\text{Total operating time} - \text{down time}}{\text{Number of Failures}}
\] (3)

2.2.3 \textbf{Availability}

Availability is the level to which a component or system is accessible and operational at the time when needed. Usually impacted by MTTR and MBTF

\[
\text{Availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} = \frac{1}{1 + \lambda \tau}
\] (4)

Where;

\[
\lambda = \text{failure rate}
\]
\[
\mu = \text{repair rate}
\]
\[
\tau = \text{duration of outage}
\]

MTTF = the time from the end of failure episode \( n \) to the beginning of failure episode \( n + 1 \)

MTBF = the time from the start of failure episode \( n \) to the beginning of failure episode \( n + 1 \).

Equations formulated in (1) to (4), gave the reliability indices calculations for MTTR, MTBF, and Availability. Tables 1 and 2 show the results obtained.
Table 1: Data and reliability indices for 2015

| Month | Operating time (No of hrs. /yr.) | No of consumers (NT) | Frequency of Outages (Ni) | Downtime (Hrs.) | MTBF (hr.) | MTTR (t)/hr. | Repair rate (μ)= I/τ | Failure Rate (Fails/yr.) | Availability, A (%) |
|-------|----------------------------------|----------------------|---------------------------|-----------------|------------|--------------|-------------------|------------------------|------------------|
| Jan   | 744                              | 1180                 | 0                         | 0               | 0          | 0.428        | 0.998             | 0.998                  |
| Feb   | 672                              | 1180                 | 0                         | 0               | 0          | 0.428        | 0.997             | 0.998                  |
| Mar   | 744                              | 1180                 | 0                         | 0               | 0          | 0.428        | 0.997             | 0.998                  |
| Apr   | 720                              | 1180                 | 0                         | 0               | 0          | 0.428        | 0.997             | 0.998                  |
| May   | 720                              | 1180                 | 3                         | 1.25            | 247.58     | 0.42         | 2.4               | 0.004                  |
| June  | 720                              | 1180                 | 0                         | 0               | 0          | 0.428        | 0.997             | 0.998                  |
| July  | 744                              | 1180                 | 5                         | 1.83            | 148.43     | 0.37         | 2.73              | 0.007                  |
| Aug   | 744                              | 1180                 | 0                         | 0               | 0          | 0.428        | 0.997             | 0.998                  |
| Sep   | 720                              | 1180                 | 1                         | 0.5             | 743.5      | 0.5          | 2                 | 0.004                  |
| Oct   | 744                              | 1180                 | 0                         | 0               | 0          | 0.428        | 0.997             | 0.998                  |
| Nov   | 720                              | 1180                 | 0                         | 0               | 0          | 0.428        | 0.997             | 0.998                  |
| Dec   | 744                              | 1180                 | 0                         | 0               | 0          | 0.428        | 0.997             | 0.998                  |
| Average | 0.75                         | 0.29                | 379.84                   | 0.428           | 2.377      | 0.005        | 0.998             |
| TOTAL | 9                                | 3.58                | 1139.51                  | 1.28            | 7.13       | 0.015        | 2.995             |

Table 2: Micro-grid reliability indices for the five years considered.

| Year | Frequency of outages | Downtime (Hrs.) | MTBF | MTTR | Availability |
|------|----------------------|-----------------|------|------|--------------|
| 2015 | 9                    | 3.58            | 379.839 | 0.428 | 0.998       |
| 2016 | 19                   | 10.58           | 202.799 | 0.428 | 0.997       |
| 2017 | 40                   | 37.27           | 240.433 | 0.936 | 0.997       |
| 2018 | 100                  | 51.2            | 90.884  | 0.499 | 0.994       |
| 2019 | 34                   | 16.3            | 224.139 | 0.499 | 0.998       |

3. Results and Discussion

The data collected for 2015 evaluated using equations 1 to 4, and the reliability indices analysis results are as shown in table 1. The one for the subsequent years of 2016 to 2019 were also analyzed in a similar way. The evaluation of 2015-2019 data collected from the microgrid gave the reliability indices; Availability (A), MTTR, MTBF, downtime, and frequency of outages. Table 2 shows a summary of the result, and Figure 3 to 7 shows the pictorial result of the micro-grid performance over the five years.
Fig. 3: Micro-grid downtime per Year

Fig. 4: Micro-grid availability variation per Year
Fig. 5: Micro-grid MTTR variation per Year

Fig. 6: Micro-grid MTBF variation per Year
Figure 3 showed that the downtime of the micro-grid in 2018 had the highest downtime hours with a value of 51.2hrs, while 2015 had the lowest of just 3.58hrs, which showed a direct relationship to the frequency of outages in Figure 7 with the highest number of interruption of 100. The mean time to repair (MTTR) ranges from 0.43 to 0.94 hours, as seen from Figure 5, with the year 2015, having the lowest value and 2017 having the highest. This result indicates that when the microgrid went off in 2017, it took more time to put it back to regular operation and meet the power demand of the community. Therefore, the reduction in the hours of MTTR increases the supply hour and also increases availability, thereby ensuring a more reliable network. The results of this study also showed that the availability of the micro-grid system was very high in both 2015 and 2019, having a value of 99.8% with the lowest in 2018, as shown in Figure 4.

Figure 6 showed the MTBF with the highest value of 379.8hrs in 2015 and the lowest in 2018, which followed a similar variation as availability. Figure 7 showed that 2018 recorded the highest frequency of outages and the smallest in 2015. Data from Figures 4, 6, and 7 show that in 2018 there was minimal MTBF and availability due to the high rate of outages, which implies that the increase in the frequency of outages reduces the value of availability and the Mean Time Before Failure (MTBF).

In general, the rate of interruption in this study is low, providing very high availability for most of the years except during faults or adverse environmental conditions such as a thunderstorm.

4. Conclusion
The reliability study of a micro-grid system is very critical because it gives a true reflection of the performance, quality, and standard of the grid. Monthly outage and the outage duration data collected was collected and used to evaluate the reliability of a typical Obayantor community in Edo state for five years. The data collected were evaluated using the analytical method to obtain the reliability indices such as the downtime, frequency of outages, availability, MTTR, and MTBF.
The analysis shows different results for the availability, downtime, MTTR, MTBF, and frequency of outages, respectively, over the years under consideration. The reliability of the micro-grid improved because of the inclusion of a diesel generator and the battery bank, thereby nullifying the intermittency associated with the stochastic nature of the solar PV system. The power supply was available. Except for the year 2018, when there was a significant fault. The result obtained from data analysis, as seen in the charts, revealed that the microgrid had the highest frequency of outages in the year 2018 with the least availability 99.42% corresponding to the highest number of outages value of 100.

Conflict of Interest: The authors declare at this moment that there is no conflict of interest.

Acknowledgments: Authors express their appreciation to Covenant University for sponsoring this research.

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