INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
D. Widjajanto et al., Vol.9, No.4, December, 2019

Nanogrid Reliability Assessment Study Using Loss of Load Expectation

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Received: 28.08.2019 Accepted: 01.10.2019

Abstract - Microgrids are autonomous electric power distribution systems for small communities that utilize distributed generation to improve performance. Various microgrid advantages, such as increased reliability, efficiency, etc. are causing its penetration to the electric power system to be increased every day. Currently, microgrid applications have evolved to a smaller scale called nanogrids. The objective of this research is to promote a method that can be used to asses the reliability of a various nanogrid system using loss of load expectation (LOLE), a well known and established reliability analysis method for power system. The increasing number of microgrids and nanogrids raises the need for a tool that can be used to assess their performance. This method would be used as a tool to compare one nanogrid system to another and to measure the ups and downs of a system's performance over time or after an improvement has been made. As a validation, this method will be used to evaluate the reliability of nanogrids in the energy management laboratories, physics engineering study programs, the Institut Teknologi Bandung.

Keywords microgrid, nanogrid, reliability analysis, LOLE, Markov model.

1. Introduction

The term microgrid has its own meaning in the world of electricity. A microgrid is a single controlled unit in a power system that can be operated as a single aggregated load. The unit is made up of one or more distributed generators to supply local loads equipped with power electronic interfaces like inverters, energy storage, a network of energy distribution lines, communication lines, and a control center that monitors and controls the operation of the system as shown in Fig. 1. The prevalence of microgrids is due to the many benefits that can be provided such as reduced operating costs, the use of clean renewable energy, and increased system reliability [1]. The most popular renewable sources of microgrids are solar and wind energy [2], [3]. Based on the type of voltage used in the energy flow line, microgrid can classified into two types namely AC microgrid and DC microgrid [4]. Each type has its own strengths and weaknesses. Microgrid reliability can be improved by connecting microgrids with main utilities and energy storage systems.

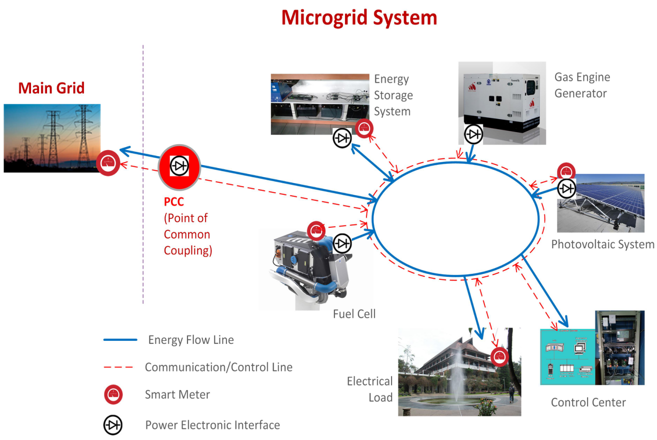


Fig. 1. Illustration of microgrid system

Along with the smart grid infrastructure concept of microgrids allows the ability to exchange power between microgrids with the main grid system [1]. There are two operating modes of a microgrid namely "island mode" and "connected mode" [2], [4]. In "island mode" microgrid operates independently, that is completely separated from the main power system. It is called "island mode" because, in this mode, the microgrid is considered as a small island separated from the main land. The main land is the main electric power system unit that is connected to the microgrid. In "connected mode" the microgrid is connected to the main network. The point that becoms connecting gate between microgrid and the other grid is often called Point of Common Coupling (PCC) [4]. From the main electric power system viewpoint, microgrid in a connected state is seen as a special entity that can act as a source and as a consumer of main electric power system.

There are three conditions required for a distributed generation that supplies local loads to be called a microgrid or nanogrid, namely [2]:

- There must be electrical boundaries that are clearly defined.
- There must be a control center that controls the operation of the system.
- The installed capacity of the distributed generation must be greater than the size of the peak critical load it serves so it is possible to operate independently, without support of the other electric power systems.

A nanogrid is a microgrid on a smaller scale [5]. Nanogrid research is relatively new, but it is getting a lot of attention, as seen by the increasing number of Elsevier and IEEE papers that discuss this topic

Burmester [5] defines a nanogrid as "An electric power distribution system in a building unit with the ability to be connected or disconnected from another electric power distribution system through a gateway". The capacity of a nanogrid is generally quite small, i.e. no more than 10kW [5].

The nanogrid concept that utilize locally available renewable energy sources become the most ideal solution to electrify a remote small community that are not affordable by the main electricity grid. References [6] examines the use of various renewable energy sources to electrify a remote area inhabited by small communities. The results of the study recommend that the choice of renewable energy sources used is highly dependent on the local situation, especially the availability of renewable energy resources type in that area. References [7] evaluates nanogrid systems that use solar energy sources to fulfill domestic household electrification needs. The evaluation results state that the cost of electrification using this method is 50% cheaper than conventional electrification.

The purpose of a power system is to serve the customer's electricity needs with good quality but at an affordable price. To fulfil this requirement, a performance analysis is very important, namely, to measure to what extent the purpose of the electric power system is achieved.

One kind of performance that needs to be measured is reliability. Reliability is defined as the probability of a device to adequately function according to its purpose during its operational time under normal operating conditions [8]. The results of the microgrid system reliability analysis are very useful inputs in the decision-making process of planning, operating, and maintaining a microgrid [9], [10].

As a power system, the reliability of a nanogrid can be approached from several points of view such as adequacy, security, and quality. In accordance with the purpose of the power system, the most important point of view, in terms of reliability, that should be analyzed is the adequacy reliability. Adequacy analysis assesses the ability of the system to supply energy to consumers as needed. Any failure of the system to meet these demands reduces the reliability value. This study will focus on adequacy analysis.

The variation in microgrid or nanogrid configurations is vast, far more than in conventional power systems. This is due to the implementation of some new concepts and technologies that have never existed before, including the decentralization of generation with the use of distributed energy sources, the intensification of the use of ICT (Information and Communications Technology), and the decentralization of control by enabling island mode.

From the perspective of renewable energy practicians, an assessment of the reliability of nanogrid or microgrid systems is important because, in reality, most implementations of renewable energy use are carried out using the concept of microgrids. By evaluating the reliability of microgrid or nanogrid systems, optimal use of renewable energy can be maintained.

At present, studies on microgrid reliability are still limited. As far as the author's knowledge, there is no one method of assessing reliability that is comprehensive enough so that it can be used to assess the reliability of various configuration microgrid. Most of the methods offered are only capable to assess certain important aspects of the microgrid system and can only be used to assess microgrid systems that have a similar configuration. On the contrary, LOLE indicator can be used to measure almost all kind configuration of microgrid system. This study illustrates how LOLE is used to measure the reliability of a nanogrid. With this study it is hoped that renewable energy practitioners can utilize this method to optimize microgrid networks

Research on microgrid reliability has been carried out for several years. The effect of operating conditions on microgrid reliability indices was investigated in [11]. Evaluation of the level of availability of microgrid systems with priority loads using the simulation-analytical hybrid method was proposed in [12]. Youli and Nagasaka [13] proposed a laboratory-based evaluation method for microgrid reliability using the Monte Carlo simulation. Predictions of microgrid reliability, based on the operation of the protection system, were analyzed in [14]. A microgrid reliability evaluation that focused on customers was proposed in [15]. Georgilakis et al. [16] evaluated, from an economic point of view, the reliability of a microgrid that used only renewable energy. Reliability analysis of wind power systems was assessed in [17], [18].

Reliability analysis of solar power systems was studied in [19], [20], [21]. An evaluation model of microgrid reliability that treats a distributed generator as an active agent, not as a decentralized generator, was proposed in [22]. Evaluation of the availability of microgrid power during natural disasters was reviewed in [23]. Yokoyama [24] proposed a special reliability indicator to assess the power supply reliability of a microgrid that used only solar and wind power. Ahmed et al. [25] proposed to decentralize controls on the microgrid system to increase its reliability. Furthermore References [21] proposes a method for predicting the performance of photo voltaic generation systems using ANN and Mesh Networks based on climatological parameters data and PV generation data at inverter level. The result of prediction process is the estimation of DC current output generated by inverter with a prediction accuracy level of 93.9%

None of these papers explicitly carried out a reliability analysis of the nanogrid system. However, this is not too problematic because the microgrid and nanogrid structures are basically the same; therefore, the reliability analysis method developed for microgrids, in general, will also be able to be implemented on nanogrid systems. This research proposes the use of the LOLE indicator to measure the reliability of the nanogrid system. Although research related to the reliability of the nanogrid system is still at an early stage, the need for a tool that can be used to assess the reliability of the nanogrid system is very urgent.

The paper is organized as follows. In section 1, the concept of microgrid and nanogrid and the importance of reliability analysis of the system is introduced. Matters related to the analysis of the power system are explained further in section 2. More specifically, this section explains how the LOLE indicator is used as a tool to analyze the reliability of the power system. Section 3 presents how to construct a Markov model for the nanogrid system which is the object of this study. Section 4 shows reliability analysis on nanogrid systembeing studied using the LOLE indicator. The results and discussion of case studies are presented in section 5. Finally, the conclusion is summarized and presented in section 6.

2. Reliability Analysis of Power System

Reliability is defined as the probability of a device to function according to its purpose adequately during its operational time under normal operating conditions [26], [21], [27]. Viewed from the perspective of power system operator, reliability studies are very important because it enables them to find out the frequent cause of faults and the areas that are susceptible to faults [28]. Basically, there are two main assessment reliability methods, the historical assessment, and predictive assessment [28]. This paper only discusses historical assessment of nanogrid reliability

In many cases, the behavior of systems, including electric power systems, cannot be precisely defined and can only be expressed with probability values. For example, we cannot ascertain when a component in the system will be damaged; we can only say that it is very possible that the component will be damaged after operating for a certain period of time (the technical term for this is mean time to failure/MTTF). The reliability of a power system can be interpreted as the probability that an electric power system is able to meet the needs of its customers throughout the planned operating time.

.The main concern for reliability analysis is the failure event that has the potential to cause interruptions. Failure can be classified into two types namely active failure and passive failure. Active failure is a failure that provides a direct danger to the power system which if left unchecked it will cause very serious damage and maybe even a blackout. Active failure must be stopped immediately by the existing protection system to minimize the serious danger. Example of active failure is the occurrence of a short circuit on one part of the network. Passive failure is the opposite of active failure, which is a failure that does not cause direct harm to the power system. Passive failure may last a long time without affecting the system for a long time. An example of passive failure is damage to a breaker which result in it cannot work properly.

One of the most expected benefits of implementing a microgrid or nanogrid system is the improvement of efficiency and reliability [2]. It should be noted that the fulfillment of this expectations significantly depend on the proper size and location of distributed generators unit [29]. The optimal size and location of distributed generators will produce benefits such as compensating the reactive power to achieve voltage control, reducing the transmission loses, preventing interruption due to an increase in spinning reserve, and the use of renewable energy sources that are economical and environmentally friendly. Conversely, non-optimal size and location of distributed generators will dramatically decreases the level of reliability and increases losses [29].

2.1. Stages of Reliability Analysis

There are two choices of approach that are used to analyze system reliability, namely analytical methods and simulation methods [8], [30]. The method used in this paper is classified as an analytical approach. The work stages included in analyzing the adequacy reliability of a nanogrid are as follows:

- Determine the reliability indices to be used
- Make a reliability model of this nanogrid system
- Gather the required data according to the model used
- If it is necessary to improve understanding of system behavior, a case study can be conducted to compare various scenarios that might be implemented.
- Carry out analysis based on the model and data that has been set
- Formulate conclusions to get a better understanding of the system being analyzed. A better understanding of the system will be very useful in an effort to improve or develop such a system.

2.2. Power System Reliability Indices: LOLE

One of the unique qualities of the electric power system is that the energy produced must be used immediately because the cost of storing electricity power is still very expensive. For economic and efficiency reasons, the amount of electricity produced must be adjusted to demand at all times. This is not an easy thing to do because the magnitude of the electrical load changes naturally at any time and at random.

Energy production that is too large in comparison to needs is an unnecessary waste, even as a loss. On the contrary, if at one time the production of electric power is smaller than the need, there will be an interruption in power for some consumers; even if it is not overcome, it can cause a total blackout on the system power. Consequently, the power system manager must strive to ensure that these two things can be compromised (optimized).

The implementation of the power system must be able to ensure that the power generation capacity is sufficient for the electricity needs throughout its operational time frame. LOLE is one of the reliability indicators that is right for this purpose. As the name implies, LOLE quantifies the amount of the occurrence of loss of load on the power system. Loss of load is when the amount of the system load exceeds the generation capacity. The smaller the LOLE value, the better the reliability of the power system.

There are two possible reasons that may cause a loss of load event. First, it is caused by the failure of one of the main components, resulting in an outage to the component. The outage makes the generating unit unable to produce energy, which in turn, reduces the system's generating capacity at that time. The second possibility is the occurrence of a peak load surge, beyond the original estimate, so that it exceeds the generation capacity at that time.

LOLE estimates the duration of loss of load on a power system in a certain period of time (usually one year) by taking into account the stochastic data of the system in question. There are four steps to calculate LOLE, namely:

1. Make a generation capacity model
2. Make a load model
3. Combine the generation capacity model and load model to get a risk model
4. Calculate the reliability index

The time unit used to measure LOLE is usually hours per year, days per year, or days per 10 years. The minimum standard that is often used for commercial power systems is one day per 10 years [31], which means that the cumulative amount of loss from load in a generating system that can still be tolerated is one day in 10 years. The LOLE unit can be converted to Loss of Load Probability (LOLP) units by multiplying the LOLE value by 100%. Therefore, one day per 10 years LOLE is converted to LOLP and becomes 0.027%.

LOLE can be calculated by combining a load model with its generator model. In this paper, the load model is represented by the Load Duration Curve (LDC) and the generation model is represented by Capacity Outage Probability Table (COPT). The formal equation for calculating LOLE power systems in a period of operation is given by

$$LOLE = \sum_{i=1}^{N} P_i(C_i - L_i) \quad days/period \tag{1}$$

where *i* is day in the assessment period, *N* is number of days in the assessment period, C_i is availability system capacity on day *i*, L_i is forecast peak load on day *I*, and $P_i(C_i - L_i)$ is probability of loss of load on day *I (* i.e., probability that *Li* > *C)*.

There is a very close relationship between load demand and the outage probability of a power system; the greater the load demand at any given time, the greater the probability of outage in a system. This principle is used to calculate LOLE values. Related to this phenomenon, equation (1) can be expressed to

$$LOLE = \sum_{j=1}^{M} f_i P_j(L_j > C_j) \quad days/period \tag{2}$$

where *j* is the time segment (group of days) in which the power system has the same outage probability, *M* is the number of days group that have the same outage probability, f_i is frequency of the number of days in time segment *j*, C_j is available capacity on days group *j*, L_j is load demand in the time segment *j*, and $P_j(L_j > C_j)$ is the probability of loss of load on days group *j* (i.e., probability that $L_j > C_j$).

The time unit chosen to calculate LOLE value is determined based on the situation of the power system to be assessed. Generally, the load fluctuation of a nanogrid system in a day is high, so it would be more appropriate to use an hour as the unit of time instead of a day. In this research, the assessment period is set to a year, so that the LOLE value is expressed in an hour/year unit.

The value of loss of load probability of a power system at time group P_j depends on the amount of the load at that time and on the probability of losing generation capacity, which is represented, in this case, by a capacity outage probability table. Further discussion about COPT will be presented by the example in section 4.

3. Markov Model for Nanogrid being studied

After determining which reliability indices are to be used, the next step is developing the reliability model. The model commonly used for this purpose is the Markov model [26]. The Markov model is used to evaluate the influence of generating units on power system reliability; in this case, it determines adequacy indices by considering the failure rates and repair rates of the components. The overall nanogrid reliability can be estimated by analyzing the reliability indicators of the main components separately. By using the Markov model, the stochastic, or random, nature of the failure of the main components can be analyzed. The Markov model defines the operation of the system or component into several states equipped with the probability value of moving from one operational status to another operational status.

One of the parameters needed to perform adequate analysis is the value of availability (A) and unavailability (U) of the main components of the system that support overall system reliability. Availability can be interpreted as the probability that a system or component is in a normal state during its operation [8]. On the contrary, unavailability is the probability that it is in an abnormal state or a state of disturbance. Therefore, for every system or component, the sum between its availability and unavailability always results in a value of 1 or 100%. The values of these parameters can be obtained using the Markov model in equations (3) – (5) [32].

$$A=\frac{\sum uptime}{\sum uptime+\sum downtime}=\frac{m}{m+r}=\frac{1/\lambda}{1/\lambda+1/\mu}=\frac{\mu}{\lambda+\mu} \tag{3}$$

$$U=\frac{\sum downtime}{\sum uptime+\sum downtime}=\frac{r}{m+r}=\frac{1/\mu}{1/\lambda+1/\mu}=\frac{\lambda}{\lambda+\mu} \tag{4}$$

$$A+U=1 \tag{5}$$

where λ is failure rate, μ is repair rate, m is mean time to failure (MTTF), r is mean time to repair (MTTR), and $m+r$ is mean time between failure (MTBF). In the case of a system that can be represented by the Markov model, there are inverse relationships between λ and μ and with r and m, namely $\lambda = 1/m$ and $\mu = 1/r$.

This study offers a performance evaluation method for nanogrid reliability using conventional methods that are commonly used in power system reliability assessment. To validate the method, it will be used to assess a nanogrid in the energy management laboratory, engineering physics department, Institut Teknologi Bandung. Fig.2 shows the configuration of this nanogrid.

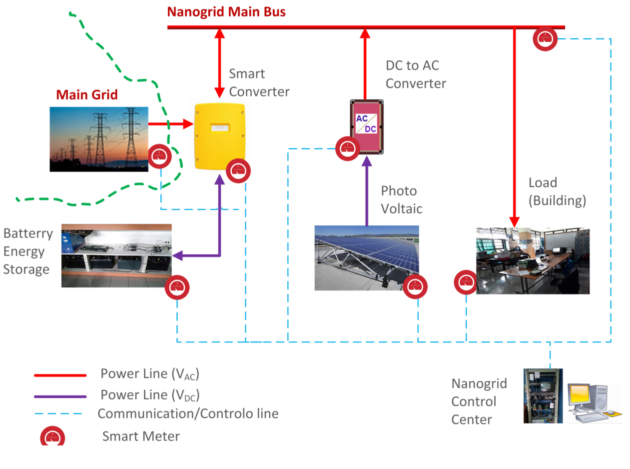
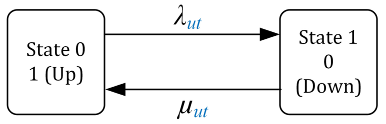


Fig. 2. Schematic diagram of the nanogrid system in the Energy Management Lab - Engineering Physics ITB.

Viewed from a reliability perspective the nanogrid being reviewed (as shown in Fig.2) can be grouped into four reliability entities. Each entity can be modelled into the Markov reliability model, i.e., the Markov model for main utility, smart converter, battery energy storage, and photovoltaic system. Fig.3 shows the Markov model for Main Utility or Main Grid.



Subscript : ut
Symbol : # (digit)
Value 0 → Main Utility on Down state
Value 1 → Main Utility on Up state

Fig. 3. Markov model for main utility.

The availability and unavailability values of the main utility power supply (A_{ut} and U_{ut}) can be obtained using equation (6)

$$A_{ut}=\frac{\mu_{ut}}{\lambda_{ut}+\mu_{ut}} \quad \& \quad U_{ut}=1-A_{ut} \tag{6}$$

The Markov model for Smart Converter (subscript: *sc*) and the Markov model for Battery Energy Storage (subscript: *es*) are the same as the Markov model for Main Utility. The Markov model of photovoltaic system is shown in Fig. 4.

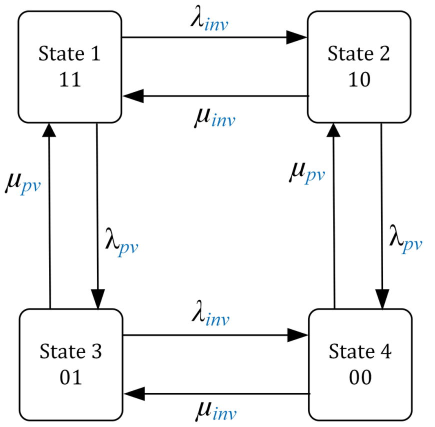


Fig. 4. Markov model for photovoltaic system (*pvs*).

In the Markov model of the photovoltaic system, there are two types of operating conditions that are reviewed, namely the operating conditions of the photovoltaic system (subscript: *pv*) and the operating conditions of the inverter (subscript: *inv*). There are only two possible statuses in the photovoltaic system and inverter, namely the normal operating status, or Up status, which is symbolized by the digit "1" and the failure status, or Down status, which is symbolized by the digit "0". In the figure above, the first digit indicates the operating condition of the photovoltaic, and the second digit indicates the operating condition of the inverter.

The reliability of the PLTS system depends on the operating status of its constituent components, namely the photovoltaic and inverter. Judging from the reliability viewpoint, these two components are arranged in series, meaning that the PLTS system can operate normally only when both components are in a normal operating state. If one or both of these components are interrupted, the PLTS is unable to operate (turn to down state). The transition probability matrix for this PV system is as follows

$$P_{pvs} = \begin{bmatrix} 1-\lambda_{inv}-\lambda_{pv} & \lambda_{inv} & \lambda_{pv} & 0 \\ \mu_{inv} & 1-\lambda_{pv}-\mu_{inv} & 0 & \lambda_{pv} \\ \mu_{pv} & 0 & 1-\lambda_{inv}-\mu_{pv} & \lambda_{inv} \\ 0 & \mu_{pv} & \mu_{inv} & 1-\mu_{inv}-\mu_{pv} \end{bmatrix} \tag{7}$$

This photovoltaic system can operate normally (up state) only in state 1, and in states 2, 3 and 4, the system is down. It can be concluded that states 2, 3, and 4 are absorbing states. Therefore, the truncated matrix is $Q = 1 - \lambda_{inv} - \lambda_{pv}$ [32].

The main time to failure of PLTS (m_{pvs}) can be calculated using expression $[1-Q]^{-1}$ [31] [26], so the equation becomes

$$\begin{aligned} m_{pvs} &= \left[1-(1-\lambda_{inv}-\lambda_{pv})\right]^{-1} \\ &= \left[\lambda_{inv}+\lambda_{pv}\right]^{-1} \\ &= \frac{1}{\lambda_{inv}+\lambda_{pv}} \end{aligned} \tag{8}$$

And the failure rate of the photovoltaic system can be calculated as

$$\lambda_{pvs} = 1/m_{pvs} = \lambda_{inv} + \lambda_{pv} \tag{9}$$

Considering the nature of the relationship between reliability of the photovoltaic and inverters is serialized, the availability of the photovoltaic system as a whole can be calculated as

$$\begin{aligned} A_{pvs} &= A_{pv} \cdot A_{inv} \\ &= \left(\frac{\mu_{pv}}{\mu_{pv}+\lambda_{pv}}\right) \cdot \left(\frac{\mu_{inv}}{\mu_{inv}+\lambda_{inv}}\right) \end{aligned} \tag{10}$$

The unavailability value of the battery energy storage system can be obtained by

$$U_{pvs} = 1 - A_{pvs} \tag{11}$$

Using equations (3) and (12), the PLTS system repair rate of photovoltaic system (μ_{pvs}) can be calculated as follows

$$\begin{aligned} A_{pvs} &= \frac{\mu_{pvs}}{\lambda_{pvs}+\mu_{pvs}} \\ &= \left(\frac{\mu_{pv}}{\mu_{pv}+\lambda_{pv}}\right) \cdot \left(\frac{\mu_{inv}}{\mu_{inv}+\lambda_{inv}}\right) \end{aligned} \tag{12}$$

$$\mu_{pvs} = \frac{\left(\lambda_{pv}+\lambda_{inv}\right)\cdot\left(\lambda_{pv}\cdot\mu_{inv}\right)}{\lambda_{pv}\mu_{inv}+\lambda_{pv}\mu_{inv}+\lambda_{iniv}\mu_{pv}} \tag{13}$$

4. Case Study

To obtain a better understanding of the behavior of the system reliability being studied, several configuration scenarios will be tested and analyzed, and the results for each configuration will be compared to one another. There are four scenarios that will be tried in this research, namely:

1. The system is served by one source only, namely the main grid.
2. The nanogrid is served by two sources, namely the main utility and a photovoltaic system.
3. The nanogrid is served by two sources, namely the main utility and a battery energy storage system.
4. The nanogrid is served by three sources, namely main utilities, a photovoltaic system, and a battery energy storage system.

The technical specifications of each main component of the nanogrid system are shown in the Table 1.a and 1.b. This data will be used to calculate the LOLE value for each scenario. From the results, a comparison of reliability for each scenario can be made. The results of this comparison can be used as information material for future system development.

Table 1.a. Technical parameter of the nanogrid system

Parameter	Main Utility	Photovoltaic System	Battery
Installed Capacity	2000 Watt	1000 Watt	9.6 kWh
Nominal Capacity	2000 Watt	1000 Watt	800Ah 12 Volt
Service Life	-	20 tahun	4 tahun
Efficiency	99 %	19 %	80 – 90 %
Failure Rate (f/y)	5.3	0.4	0.039
Repair Rate (r/y)	73	18.25	57.63

Table 1.b. Technical parameter of the nanogrid system (continued)

Parameter	Smart Converter	Inverter
Installed Capacity	4 kWatt	2 kWatt
Nominal Capacity	4 kWatt	2 kWatt
Service Life	25 tahun	20 tahun
Efficiency	98 %	99 %
Failure Rate (f/y)	0.0271	0.143
Repair Rate (r/y)	62.5	52.143

Every minute SCADA (Supervisory Control and Data Acquisition) system of the nanogrid being review acquires data of electrical power load. Due to the hourly unit time used in this case, the data per minute are averaged for each one-hour period, so there are 8760 load data obtained for one year, 2017. From these data we can obtain the load duration curve profile as shown in the Fig. 5.

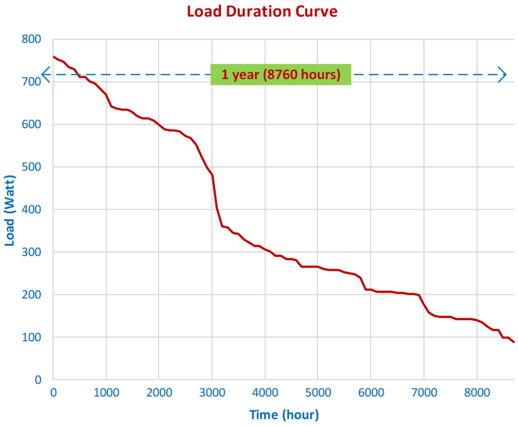


Fig. 5. Load duration curve of the nanogrid system under assessment period of 2017.

4.1. Case study 1: LOLE calculation of system with single source, i.e., from main grid

Power system configuration for case 1 is shown in Fig. 6.

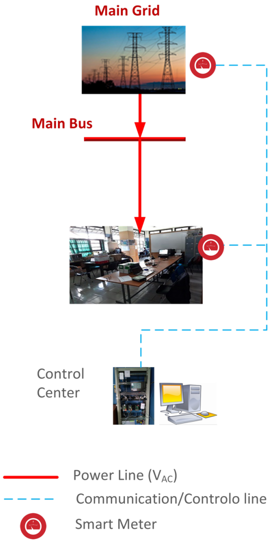


Fig. 6. System configuration for case study 1.

Reliability analysis in this study considers only the adequacy between power supply and demand, i.e., the equilibrium between power supply and demand. It has not yet taken into account the influence of distribution systems and other factors; therefore, the power system balance model is only determined by the total system generation and total load. The equilibrium model between load and generation is shown in Fig.7 as follows

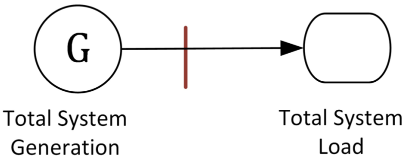


Fig. 7. System adequacy model.

In case 1, the stochastic characteristics of the total system generation can be represented by the value of availability and unavailability. From Table 1.a. it is known that the value of the failure rate from the main utility (λ_{ut}) is 5.3 (failure/year) and the repair (μ_{ut}) is 73 (repair/year). The availability and unavailability of total system generation can be calculated using equation (3). The calculation results are A = 0.93, and U = 0.07. Because the power supply system comes only from this one source, the LOLE system can be calculated easily, i.e., simply multiplying the value of unavailability by its assessment period (one year or 8760 hours), and the result is 613.2 hours/year or 25.55 days/year.

4.2. Case study 2: LOLE calculation of a nanogrid with two sources, i.e., main grid and a photovoltaic system

Power system configuration for case 2 is shown in Fig. 8 as follows

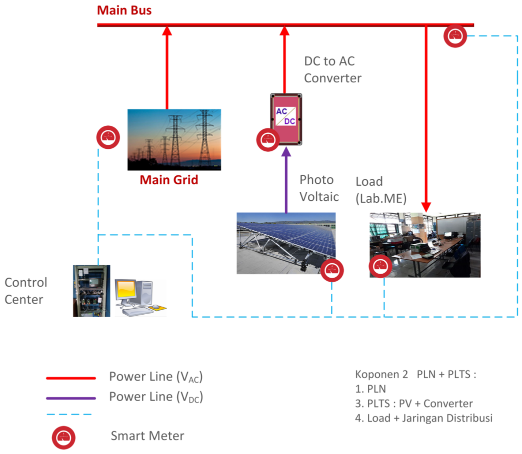


Fig. 8. System configuration for case study 2.

Fig. 9 shows the configuration of a nanogrid system in this case, which is seen from the reliability analysis perspective.

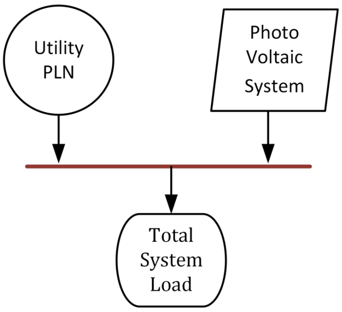


Fig. 9. Adequacy representation of case 2.

In cases 2, 3 and 4, because the number of electrical power supplies is more than one, the stochastic characteristics of total system generation are more precisely represented by using a COPT. A COPT combines the value of generation capacity and availability of each generating unit to estimate the generation capacity and availability of the whole system [31].

The most simple and intuitive way to obtain a COPT is to gradually create a capacity outage table. The procedure for calculating a COPT using this method was explained in detail by Billintonn [26]. However, keep in mind that this method is only practical if there are not too many power sources. If the number of power sources is quite large (say more than 5), it would be better to use the other methods (e.g., by using the recursive algorithm) [26].

Equation (14) shows the recursive algorithm that calculates the cumulative probability at a certain capacity outage state of a system after adding a generating unit with capacity C and unavailability U. This expression is initialized by setting $P'(X)$=1.0 for $X \leq 0$ and $P'(X)$=0 otherwise [26].

$$P(X) = (1-U)P'(X) + (U)P'(X-C) \tag{14}$$

In case 2 the number of power sources is only two, namely the main utility and photovoltaic system. Availability and unavailability of the main utility has been calculated before i.e.A_{ut} = 0.93 and U_{ut} = 0.07. The availability and unavailability of the photovoltaic system can be calculated using equations (12) and (5), with a result of A_{pvs} = 0.98 and U_{pvs} = 0.02. The data needed to calculate COPT are the value of generation capacity and the availability of each power source. The generation capacity or power rate of each power source is obtained by multiplying the installed capacity value with its efficiency. The required data to calculate COPT in this case are shown in Table 2.

Table 2. The value of generation capacity and availability of power source that supply power to system in case 2

No.	Power source	Power Rating	Availability
1	Photovoltaic System	190 W (P_1)	0.98 (A_1)
2	Main Utility	1980 W (P_2)	0.93 (A_2)

Based on these data, the distribution of capacity outage probability can be calculated by enumerating all possible states with its likelihood to happen. This calculation can be summarized in Table 3.

Table 3. The procedure to calculate distribution of capacity outage probability of a power system that supplied by two power sources.

State No.	Source 1	Source 2	Capacity Available	Capacity Outage	Individual Probability
1	Up	Up	$P_1 + P_2$	0	$(A_1)(A_2)$
2	UP	Down	P_1	P_2	$(A_1)(1-A_2)$
3	Down	Up	P_2	P_1	$(1-A_1)(A_2)$
4	Down	Down	0	$P_1 + P_2$	$(1-A_1)(1-A_2)$

A distribution of capacity outage probability for systems supplied by 3, 4, or more power sources can be produced using the same procedure. However, the calculation burden will increase dramatically along with increasing the number of power sources because the states which must be calculated are equal to 2^N, with N as the number of power sources.

It should be noted that the cumulative number of probability values in the right column (individual probability) must be equal to 1. This fact can be used to check whether the calculations are correct or not. The capacity outage probability table for case 2 is shown in Table 4 below.

Table 4. Capacity outage probability table for case 2

Capacity Available	Capacity Outage	Individual Probability	Cumulative Probability
2170 W	0 W	0.9114	1.0000
1980 W	190 W	0.0186	0.0886
190 W	1980 W	0.0686	0.0700
0 W	2170 W	0.0014	0.0014

Based on COPT and LDC data of the nanogrid system, the one year or 8760 hours of LOLE period needs only to be divided into two time segments as shown in Fig. 10 below.

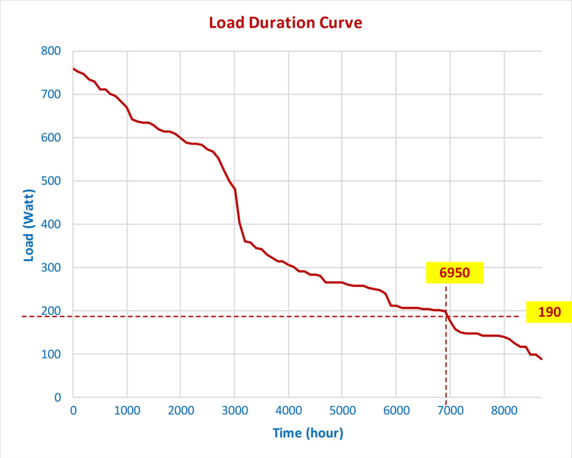


Fig. 10. Load duration curve and its time grouping of case study 2.

Data used to calculate LOLE can be summarized in table form as shown in Table 5 below.

Table 5. Data to calculate LOLE for case 2

Time Segment (j)	1	2
Time Range	Hour : 0 to 6950	Hour : 6951 to 8760
Frequency (f)	6950 hour	1810 hour
Load Range	Load ≥ 190 W	Load <190 W
Loss of load probability (P_j)	0.0700	0.0014

Determination of the loss of load probability value at certain load demand can be carried out by looking at the cumulative probability column of a COPT. For example, on table 2.c., the cumulative probability of 0.0700 coincides with the outage capacity of 1980. This means that the probability that this power system experiences an outage of 1980 or more is 7%. Likewise, the probability that this power system experiences an outage of 2170 watts or more is 0.14%

A loss of load will occur only when the capability of the generating capacity remaining in service is exceeded by the system load level [26]. Therefore, two steps are needed to determine the loss of load probability value of outage probability at certain load demand. First, we have to subtract the total capacity of the system with this load demand; this is the maximum capacity outage where the system is still able to service. Then, we must look at the COPT to find out the value that is in accordance with this outage capacity in cumulative probability column. By using this concept, we can determine that the loss of load probability is 0.0700 when the load reaches 190 watts or more and 0.0014 when the load is less than 190 watts. Then, by applying these data to equation (2), the LOLE value can be obtained, i.e., 489 hours/year or 20.38 days/year.

4.3. *Case study 3: LOLE calculation of nanogrid with two sources, i.e., from main utility (main grid) and a battery energy storage system (BESS)*

Power system configuration for case 3 is shown in Fig. 11 as follows.

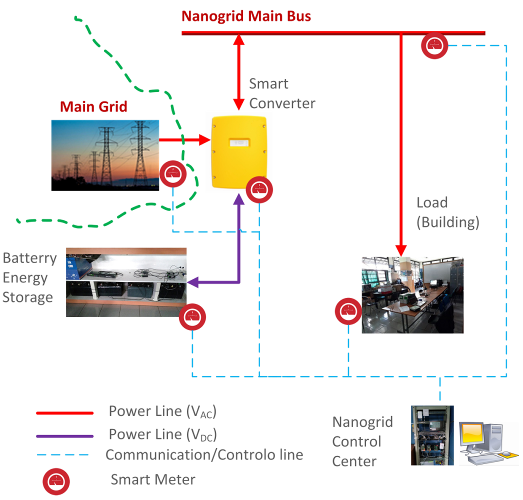


Fig. 11. System configuration for case study 3.

Fig. 12 shows the configuration of the nanogrid system in this case that is seen from reliability analysis perspective.

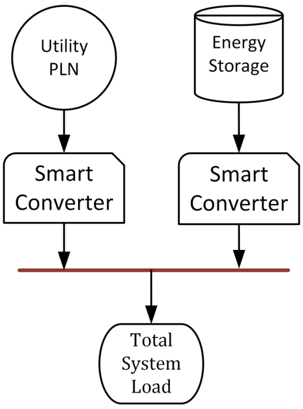


Fig. 12. Adequacy representation of case 3.

As seen in Fig.12, there is a serial relationship between the smart converter, the energy storage, and the utility. In this case, the availability value and unavailability of the two power sources can be calculated as follows

$$A_{sc} = \frac{\mu_{sc}}{\lambda_{sc} + \mu_{sc}} = 0.99$$

$$A_{es} = \frac{\mu_{es}}{\lambda_{es} + \mu_{es}} = 0.99$$

$$A_{utsc} = A_{ut} A_{sc} = 0.92$$

$$A_{essc} = A_{es} A_{sc} = 0.98$$

The required data to calculate COPT in this case are shown in Table 6 as follows

Table 6. The required data to calculate COPT case 3

No.	Power source	Power Rating	Availability
1	Battery Energy Storage	500 W	0.98
2	Main Utility	1980 W	0.92

COPT for case 3 can be calculated in the same way as before. The result is shown in table 7 as follows

Table 7. Capacity outage probability table for case 3

Capacity Available	Capacity Outage	Individual Probability	Cumulative Probability
2480 W	0 W	0.9114	1.0000
1980 W	500 W	0.0186	0.0886
500 W	1980 W	0.0686	0.0700
0 W	2480 W	0.0014	0.0014

Similar to the previous case study, in this case the one year of the LOLE period needs only to be divided into two time segments. The load duration curve and its time segments of this case are as shown in Fig. 13 below.

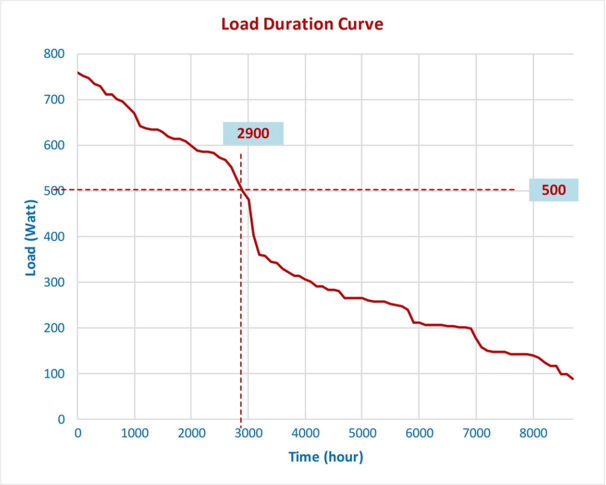


Fig. 13. Load duration curve and its time grouping of case study 3.

Data for calculating LOLE can be summarized on table form as shown on Table 8 below.

Table 8. Load data to calculate LOLE for case 3

Time Segment (j)	**1**	**2**
Time Range	Hour : 0 to 2900	Hour : 2901 to 8760
Frequency (f)	2900 hours	5860 hours
Load Range	Load > 500 MW	Load ≤ 500 MW
Loss of load probability (P_j)	0.0800	0.0016

Same as in the previous case, the LOLE value can be calculated easily using equation (2), and the result is 241 hours/year or 10.04 days/year.

4.4. Case study 4: LOLE calculation of nanogrid with three sources, i.e., from main utility (main grid), a battery energy storage system (BESS), and a photovoltaic system

Power system configuration for case 4 has been shown in section 3, Fig.2. Fig.14 shows the configuration of the nanogrid system seen from a reliability analysis perspective.

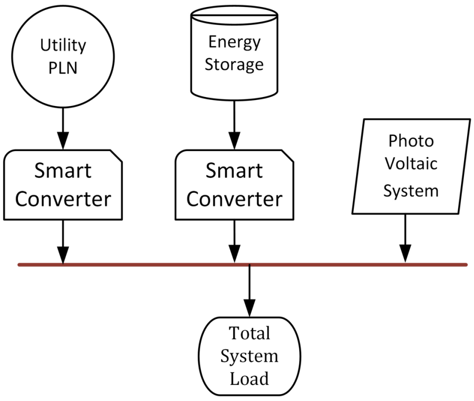


Fig. 14. Adequacy representation of case 4.

As seen from Fig. 14, in this case, the system is supplied by three power sources, i.e., main utility through smart converter, energy storage through smart converter, and from a photovoltaic system. Availability and unavailability of these power sources are denoted by A_{utsc}, U_{utsc}, A_{essc}, U_{essc}, A_{pvs}, and U_{pvs}. The values of each of these parameters have been calculated, i.e., $A_{utsc} = 0.92$, $A_{essc} = 0.98$, and $A_{pvs} = 0.98$. U_{utsc}, U_{essc}, and U_{pvs} can be calculated by using equation (5).

The required data to calculate COPT in this case are shown in Table 9.

Table 9. The required data to calculate COPT case 4

No.	**Power source**	**Power Rating**	**Availability**
1	Photovoltaic System	190 W	0.98
2	Battery Energy Storage	500 W	0.98
3	Main Utility	1980 W	0.92

The capacity outage probability table (COPT) of this system can be calculated in the same way as before. The result is shown in Table 10 as follows.

Table 10. Capacity outage probability table for case 4

Capacity Available	**Capacity Outage**	**Individual Probability**	**Cumulative Probability**
2670 W	0 W	0.9023	1.0000
2480 W	190 W	0.0184	0.0977
2070 W	500 W	0.0091	0.0793
1980 W	690 W	0.0002	0.0702
690 W	1980 W	0.0679	0.0700
500 W	2070 W	0.0014	0.0021
190 W	2480 W	0.0007	0.0007
0 W	2670 W	0.0000	0.0000

Different from cases 2 and 3, in case 4 the one-year LOLE period is now divided into four time segments. The load duration curve and its time segments as shown in Fig.15.

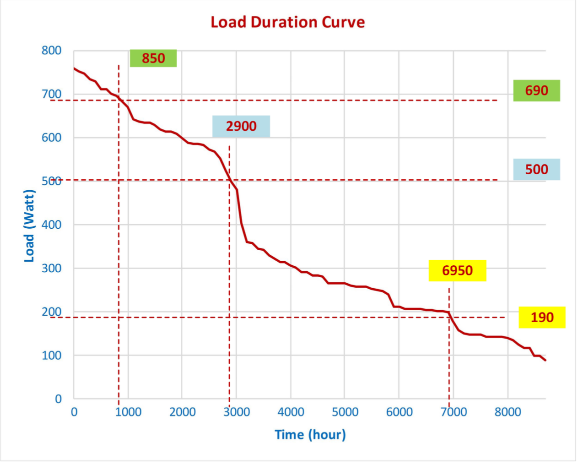


Fig. 15. Load duration curve and its time grouping of case study 4.

Based on the load duration curve and COPT, the data needed to calculate LOLE can be summarized in table form as shown on Table 11.a. and 11.b below.

Table 11.a. Load data to calculate LOLE for case 4

Time Segment (j)	**1**	**2**
Time Range	Hour : 0 to 850	Hour : 851 to 2900
Frequency (f)	850 hours	2050 hours
Load Range	Load > 690 W	Load : 501 to 690 W
Loss of load probability (P_j)	0.0700	0.0021

Table 11.b. Load data to calculate LOLE for case 4 (continue)

Time Segment (j)	**3**	**4**
Time Range	Hour : 2901 to 6950	Hour : 6951 to 8760
Frequency (f)	4050 hours	1810 hours
Load Range	Load : 191 to 500	Load <= 190 W
Loss of load probability (P_j)	0.0007	0.0000

Same as in the previous case, the LOLE value can be calculated easily using equation (2), and the result is 67 hours/year or 2.79 days/year.

5. Result and Discussion

Reliability analysis is very important in an electric power system [31], [2], [33]. The awareness of the importance of power system reliability analysis has motivated researchers to conduct research in this field, stemming back all the way to the early era of electricity use, for the benefit of mankind. Various types of power system reliability indicators and techniques to measure the reliability level of a power system have been offered by those studies [26], [33], [34], [35], [22].

However, recently, due to the development of some supporting technology, especially electric power generation technology that utilizes local renewable energy as well as information and communication technology (ICT), the development of the electric power system tends to lead to distributed generation technologies that manifest in the form of microgrid and nanogrid technology [5], [4], [15], [19].

Since it is a relatively new technology, research on the reliability analysis of the nanogrid system is limited, and publications in the field are still few; therefore, this study intends to contribute research about the reliability analysis of nanogrid systems by using a reliability indicator that is highly established and has been widely used to measure the reliability of conventional electric power systems, namely, the loss of load expectation (LOLE).

Indeed, nowadays there are some papers which specifically propose methods to assess nanogrid reliability that can measure various important aspects of the nanogrid system reliability more comprehensively. However, many of those methods focus only on specific aspects of the nanogrid that affect its reliability [36], [11], [12], [13], [14], [16] or are only suited for implementation on nanogrid systems that have similar configurations, which are not necessarily suitable to those needed elsewhere [17], [19], [24], [22], [23], [25]. However, LOLE has been proven useful in assessing the reliability of power systems with various configurations [26], [31], [37], [10].

The result of this study has shown that the LOLE indicator can also be used to measure the reliability level of a nanogrid system. Calculation results in case studies 1 to 4 have shown the implementation of the nanogrid concept is able to increase system performance quite significantly. In case 1, the system without a microgrid has a LOLE value of 25.55 day/year. After implementing the nanogrid concept by adding a photovoltaic system, its performance improved, i.e., the LOLE value went down to 20.38 day/year, and when the photovoltaic position was replaced by a storage system the LOLE value went down to 10.04 days/year. Even when the nanogrid system was equipped with both a photovoltaic system and a battery storage system, its value dropped to 2.79 day/year.

The ability of a power system to serve the entire power load demand at all times is the most important criterion that must be possessed by every electric power system [33], [24], [34], [31]. The LOLE indicator is able to measure the level of the ability of the power system to meet these criteria successfully.

Henceforth, the LOLE value can be utilized to compare the level of reliability between two power systems or to measure the up and down reliability of a power system along its operation time. If the evaluation result says that there has been a decline in LOLE value, the cause of the decline should be investigated and subsequently corrected.

The main data needed to calculate the LOLE value of a system or component is the value of its availability and unavailability [26], [31]. There are two ways to obtain availability value of a component. First if the value of the failure rate (λ) and the repair rate (μ) of the component are known, then these values can be used to calculate the value of the availability and unavailability of components using the equations described earlier. The values of the failure rate and repair rate can be obtained from various sources such as:

- The results of statistical analysis of the operational data of the system itself or similar systems that have been operating for a long time
- Generic data collected and analyzed by another organization. Certainly, the level of trust from this data is lower than data originating from previous source.
- Data listed in the specifications provided by the maker of the component or system

If all of the three sources are not available, then the MTTF and MTTR data must be calculated, as much as possible, based on the incidence of failure and repair recorded so far.

The shortcoming of the LOLE indicator is that it only measures system reliability in the past and is less appropriate if used to measure reliability at the present time or, moreover, in the future.

One thing that is important to be considered is that the LOLE calculation uses the Markov model. The requirement to use the Markov model is that the system to be modelled must only depend on its current state and not on the state before. In other words, the Markov approach can only be used on systems whose value of failure rate and repair rate can be considered constant during their operation. This can only occur if the failure distribution of the system is an exponential function. Fortunately, for some cases this assumption is valid [26].

Besides LOLE, many other commonly used indicators exist, such as [27] SAIDI, SAIFI, LOEE, EENS, etc. Heylen et al. [38] noted in their study that there are up to 129 power system reliability indicators available in various literature.

In general, most of those indicators are designed to assess reliability of conventional large-scale electric power systems with a very large number of consumers and according to the needs at that time; therefore, they are not necessarily suitable to assess reliability of the nanogrid system.

For example, SAIFI describes the average number of interruptions experienced by consumers in a certain period of time. This indicator was designed to measure the reliability of power systems involving large distribution systems that are prone to disruption. This situation does not occur in nanogrid systems; its small size means the possibility of interference with the distribution system is also small.

6. Conclusion

The level of adequacy is the most important aspect in an electric power system. LOLE is a very established reliability indicator that can represent the level of a power system's adequacy very well. This work demonstrated a method of assessing the reliability of a nanogrid connected to the main grid by using the LOLE indicator on a real nanogrid system. There are several advantages of using LOLE to measure power system reliability, including:

- The amount of input data needed to calculate LOLE are relatively low and easy to obtain compared to other more sophisticated methods suggested by several papers.
- The LOLE calculation is relatively simple and can be implemented on all nanogrid systems, regardless of its configuration.
- The LOLE is very well known as the power system reliability indices so that it becomes an effective tool for communicating reliability among the parties involved in the operation of the nanogrid system

The reliability analysis of the nanogrid system is a very important research topic. In the future, researchers must be able to formulate the more universal nanogrid reliability indicators so that they can be used to comprehensively assess reliability of various nanogrid configurations as well as the position of LOLE on conventional power systems.

However, it will take a long time and much effort to realize such indicators; meanwhile, the need is quite urgent. Therefore, through this research, the authors suggest that in the near future, and until a better alternative can be found, we use the LOLE indicator to measure nanogrid reliability.

Acknowledgements

This research was supported by the Domestic Scholarship Program of Indonesian Lecturer (Beasiswa Unggulan Dosen Indonesia – Dalam Negeri, BUDI-DN) by the Ministry of Research, Technology and Higher Education of the Republic of Indonesia.

References

[1] P. G. Mobarakeh and M. Moradian, "A New paradigm for distribution generation management considering the renewable energy uncertainties and demand response resources," *Internation Journal of Renewable Energy Research,* vol. 9, no. 1, pp. 215 - 225, March 2019.

[2] S. Parhizi, H. Lotfi, A. Khodaei and S. Bahramirad, "State of the art in research on microgrids : A review," *IEEE Access,* vol. 3, pp. 890 - 925, 10 June 2015.

[3] R. Bansal, Handbook of Distribued Generation, R. Bansal, Ed., Springer, 2017, p. 813.

[4] A. Banerji, D. Sen, A. K. Bera, D. Ray, D. Paul, A. Bhakat and S. K. Biswas, "MICROGRID : A review," in *IEEE Global Humanitarian Technology Conference (GHTC-SAS)*, Trivandrum, India, 2013.

[5] D. Burmester, R. Rayudu, W. Seah and D. Akinyele, "A review of nanogrid topologies and technologies," *Renewable and Sustainable Energy Reviews,* vol. 67, pp. 760 - 775, 2017.

[6] K. E. Okedu and M. Al-Hashmi, "Assessment of the cost of various renewable energy systems to provide power for a small community : Case of Bukha, Oman," *International Journal of Smart Grid,* vol. 2, no. 3, pp. 173 - 182, September 2018.

[7] M. M. Rafique, "Design and economic evaluation of a solar household electrification system," *Internation Journal of Smart Grid,* vol. 2, no. 2, pp. 135 - 141, 2018.

[8] R. Billinton and R. N. Allan, Reliability Evaluation of Engineering Systems - Concept and Technique, 2 ed., Springer, 1992, p. 453.

[9] P. H. Larsen, K. H. LaCommare, J. H. Eto and J. L. Sweeney, "Recent trends in power system reliability and implications for evaluating future investments in resiliency," *Energy,* vol. 117, pp. 29-46, 2016.

[10] T. Adefarati, R. Bansal and J. J. Justo, "Reliability and economic evaluation of a microgrid power system," *Energy Procedia,* vol. 142, p. 43–48, 2017.

[11] X. Xu, J. Mitra, T. Wang and L. Mu, "Reliability evaluation of a microgrid considering its operating condition," *Journal of Electrical Engineering and Technology,* vol. 11, no. 1, pp. 47-54, 2016.

[12] O. A. Ansari, N. Safari and C. Y. Chung, "Reliability asessment of microgrid with renewable generation and prioritized loads," in *2016 IEEE Green Energy and Systems Conference (IGSEC*, 2016.

[13] S. Youli and K. Nagasaka, "Monte carlo simulation method used in reliability evaluation of a laboratory-based microgrid," in *International MultiConference of Engineers and Computer Scientists (IMECS) 2010*, Hong Kong, 2010.

[14] X. Xu, T. Wang, L. Mu and J. Mitra, "Predictive analysis of microgrid reliability using a probabilistic model of protection system operation," *IEEE Transactions on Power Systems,* vol. 32, no. 4, pp. 3176 - 3184, 2017.

[15] I.-S. Bae and J.-O. Kim, "Reliability evaluation of customers in a microgrid," *IEEE Transaction On Power Systems,* vol. 23, no. 3, pp. 1416 - 1422, 2008.

[16] P. S. Georgilakis and Y. A. Katsigiannis, "Reliability and economic evaluation of small autonomous power systems containing only renewable energy sources," *Renewable Energy,* vol. 34, p. 65–70, (2009.

[17] J. Wen, Y. Zheng and F. Donghan, "A review on reliability assessment for wind power," *Renewable and Sustainable Energy Reviews,* vol. 13, no. 9, pp. 2485 - 2493, 30 June 2009.

[18] N. Tazi, E. Chatelet, A. G. Aissaoui and Y. Bouzidi, "Reliability analysis of wind turbines using petri

nets," in *7th International Conference on Renewable Enegy Research and Applications*, Paris, France, 2018.

[19] P. Zhang, W. Li, S. Li, Y. Wang and W. Xiao , "Reliability assessment of photovoltaic power systems: Review of current status and future perspectives," *Applied Energy,* vol. 104, p. 822–833, 2013.

[20] A. M. Mustafa, W. A. Omran, Y. G. Hegazy and M. Abu-Elnaga, "Reliability assessment of grid connected photovoltaic generation systems," in *4th International Conference on Renewable Energy Research and Applications*, Palermo, Italy, 2015.

[21] A. Almadhor, "Performance prediction of distributed PV generation system using Artificial Neural Networks (ANN) and Mesh Networks," in *6th IEEE InternationalConference on Smart Grid* , Nagasaki, Japan, 2018.

[22] C. L. T. Borges and E. Cantarino, "Microgrids reliability evaluation with renewable distributed generation and storage systems," in *18th International Federation of Automatic Control {IFAC} World Congress*, Milano, 2011.

[23] A. Kwasinski, V. Krishnamurthy, J. Song and R. Sharma, "Availability evaluation of microgrids for resistant pwer supply during natural disasters," *IEEE Transaction On Smart Grid,* vol. 3, no. 4, pp. 2007 - 2018, 2012.

[24] R. Yokoyama, T. Niimura and N. Saito, "Modeling and evaluation of supply reliability of microgrids including PV and wind power," in *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, 2008.

[25] A. Bani-Ahmed, M. Rashidi, A. Nasiri and H. Hosseini, "Reliability analysis of a decentralized microgrid control architecture," *IEEE Transaction on Smart Grid,* vol. 10, no. 4, pp. 1 - 9, 2019.

[26] R. Billinton and R. N. Allan, Reliability Evaluation of Power Systems, 2 ed., Springer, 1996.

[27] M. R. TUR, A. Shobole, M. Wadi and R. Bayindir, "Valuation of reliability assessment for power system in terms of distribution system, a case study," in *6th International Conference on Renewable Energy Research and Applications*, San Diego, USA, 2017.

[28] M. Wadi, M. Baysal, A. Shobole and M. R. Tur, "Reliability eveluation in smart grids via modified monte carlo simulation method," in *7th International Conference on Renewable Energy Research and Applications*, Paris, France, 2018.

[29] A. Dadkhah, N. Bayati and A. Khodadadi, "An investigation of the impact of size and location of DG on system reliability by employing sequential monte carlo simulation," *International Journal of Electrical and Elelctronic Engineering & Telecomunication,* vol. 5, no. 1, pp. 1 - 11, 2016.

[30] D. Huang, "Basic Consideration in Electrical Generating Capacity Adequacy Evaluation," University of Saskatchwan, Saskatoon, 2005.

[31] V. Pillai N., "Loss of load probability of a power system," *Journal of Fundamentals of Renewable Energy,* vol. 5, no. 1, p. 10, 2015.

[32] T. Adefarati and R. Bansal, "Reliability and economic assessment of a microgrid power system with the integration of renewable energy resources," *Applied Energy,* vol. 206, p. 911–933, 15 November 2017.

[33] Y. G. Hegazy, M. M. A. Salama and A. Y. Chikhani, "Adequacy assessment of distributed generation systems using monte carlo simulation," *IEEE Transaction On Power Systems,* vol. 18, no. 1, pp. 48 - 52, 2003.

[34] S. Wang, Z. Li, L. Wu, M. Shahidehpour and Z. Li, "New metrics for assessing the reliability and economics of microgrids in distribution system," *IEEE Transaction On Power Systems,* vol. 28, no. 3, pp. 2852 - 2861, 2013.

[35] J. V. Casteren, "Assessment of Interruption Costs in Electric Power Systems using the Weibull-Markov Model," 2003.

[36] Y. Nie, H. Liang, W. Gu, M. Wu, J. Zhu and H. Liu, "A Reliability evaluation method for distribution networks considering passive islanding detection failure," in *5th International Conference on Renewable Energy Research and Applications*, Brimingham, UK, 2016.

[37] M. Čepin, "Reliability ofpPower systems considering conventional and alternative sources of energy," in *The 10th International Conference on Digital Technologies 2014*, Zilina, Slovakia, 2014.

[38] E. Heylen, G. Deconinck and D. V. Hertem, "Review and classification of reliability indicators for power systems with a high share of renewable energy resources.," *Renewable and Sustainable Energy Reviews,* vol. 97, pp. 554-568, 2018.