Isolated Microgrid Reliability Using State Space Analysis

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Abstract. Renewable energy has grown in recent years. It has benefits to electrify islands in Indonesia, with many islands located in frontier, remote, and disadvantaged areas. Solar PV systems for source renewable energy and energy storage systems using batteries are components for an isolated microgrid. Many studies evaluate the reliability of a hybrid system and a large power using the software. This paper describes the modeling reliability of an isolated microgrid based on solar PV, battery, solar charge controller, and inverter. It presents the reliability of an isolated microgrid using state-space analysis with the Markov process. An isolated microgrid is modeled for 3 cases, where the first case does not have maintenance, the second case only has repaired for battery, and the third case has complete maintenance by the utility. It aims to present the reliability, availability and expected lifetime of the system. In this study, reliability data uses existing literature. It is calculated using MATLAB software. The sensitivity analysis is conducted to show the effect of the components' variation of failure rates and repair rates.

Keywords: *availability; expected lifetime; isolated microgrid; Markov process; state space; reliability*

1 Introduction

Indonesia is a maritime country with many islands. The electrification has reached 99.09% [1]. The remaining area that needs electricity is the frontier, remote and disadvantaged areas. One of the characteristics of electricity is that it is used at the same time as it is generated. The second characteristic is that the source generation is usually located far from consumer locations. One of the solutions is to use a microgrid. A microgrid is where source generation, load, energy storage are connected and can be controlled.

Renewable energy such as solar PV systems are integrated into a microgrid can be used to improve life and to minimize carbon footprint in the areas. In Indonesia, the target capacity installed for the solar PV systems is 6.5 GW in the year 2025 [2]. To achieve it, solar PV systems must be installed at least 30% in building state-owned and 25% in commercial buildings [1]. Indicator reliabilities are SAIDI is 10 hours/consumer/year and SAIFI is 8 occurrences/consumer/year in 2021 [3].

The reliability describes supply requirements of various loads that must not be interrupted. Reliability study relationship between probability and a measurable performance indicator such us a lifetime. Stochastic modeling is used to address the uncertainty. Risk-based decision-making techniques improve on how to quantify the operational risk and the severity of contingencies [4].

Degradation is one of many factors that affect the reliability of the system. There is research for solar PV systems that evaluate the effect of temperature and degradation rates [5] [6] [7] [8] [9]. Small domestic applications of a PV system are likely to suffer from poor quality assurance, whereas in the UK is around 96.6% [10]. Literature shows that inverter in a solar PV system is more contribute to unscheduled maintenance costs [11].

Many studies are conducted to model the reliability of a hybrid system and its financial impact [12]. The model is evaluated for steady-state availability. The reliability model is represented by block diagrams and is assessed financially by indicators related to energy and cost such as LOLP, LOLE, EENS [13] [14] [15] [16] [17] [18] [19] [20].

Many studies use the probability density function, such as exponential pdf [21] [22] and Weibull pdf [21]. Methods approaches to solve problem are Markov process [13] [23] [24] , fault tree analysis [25], Monte Carlo simulation [26] [27], FMEA [25]. The application mainly to a hybrid system [28] [20] [26] and a large solar PV system [29] [22] [27]. The research simulates the model using software, such as HOMER [30] for modeling, PRISM [24], MATLAB [6] / Simulink [31], and ReliaSoft BlockSim 9 [22] for reliability assessment.

This paper describes model reliability for an isolated microgrid. The system usually has a small power and minimum maintenance. This study uses state-space analysis with the Markov process, where the application of this method is still minimal. The paper contributions are :

1. Modeling reliability of an isolated microgrid based on solar PV, battery, solar charge controller, and inverter
2. Present reliability of an isolated microgrid using state-space analysis with the Markov process
3. Describes impact failure rates and repair rates of the energy storage system to the reliability of the isolated microgrid
4. Describes the effect of maintenance on the reliability of the isolated microgrid based on sensitivity analysis

5. Identify the expected lifetime of the isolated microgrid system.

2 Methods

This research presents a reliability analysis for an isolated microgrid. The block diagram represents the reliability of the system using boxes that reflect components and failure mechanisms. When the system has more than two possible conditions, reliability analysis can be solved by state-space analysis using the Markov process.

The behavior of one component shows the probability of the system where resides in the working state from S_0 or the failed state S_1. In the case the transitions follow an exponential distribution, the characteristic of the system depends on a constant failure rate λ_{01} and a repair rate μ_{10}. The failure process where the transition from a working state S_0 to a failed state S_1 is characterized by a constant failure rate λ_{01}. The repair process where the transition from S_1 to S_0 is characterized by a repair rate μ_{10}. [32]

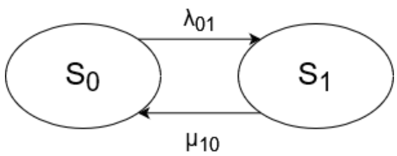

Figure 1 Representation state system from behavior of one component.

2.1 Isolated microgrid

An isolated microgrid is a microgrid with no PCC (point of common coupling) that exists and is not connected to the utility grid. An isolated microgrid can be assembled by the solar PV array, battery, solar charger controller, and inverter. A solar PV system converts solar energy to electricity. A PV cell is a semiconductor device for photovoltaic conversion. A PV module is composed of PV cells that are interconnected. These PV modules assembly a PV array with parallel or series form and generate DC voltage. An inverter is a power conditioning unit (PCU) to transform the DC output of the PV array into AC voltage. The battery is a component in a PV system for energy storage. A solar charge controller is used to control and charge the battery system. An isolated microgrid is shown in Figure 2.

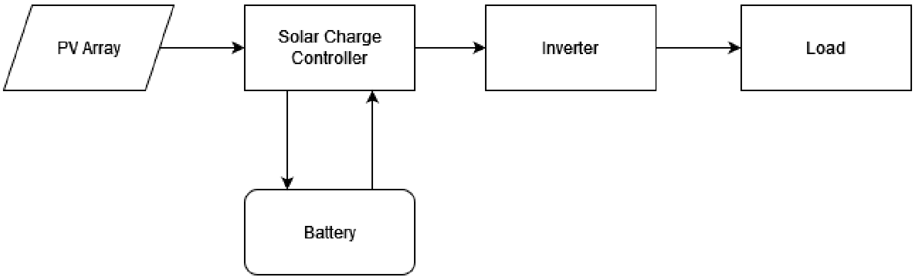

Figure 2 Isolated microgrid.

2.1.1 Reliability block diagram of an isolated microgrid

A block diagram can be used to show the reliability of an isolated microgrid. Based on the topology of an isolated microgrid, the reliability of the system can be shown in Figure 3.

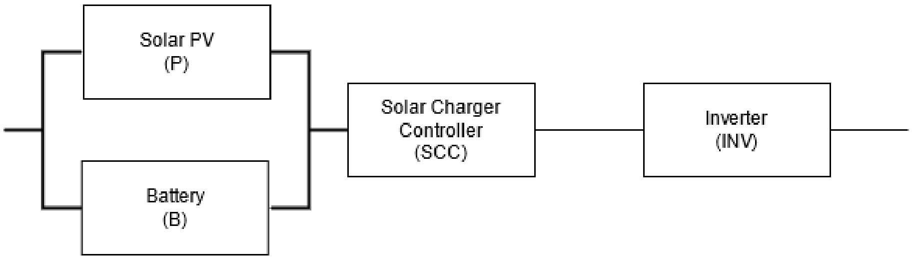

Figure 3 Block diagram of reliability of an isolated microgrid

Reliability of each component is modeled by exponential distribution and is defined by

$$R_{INV} = e^{-\lambda_{INV}\, t} \tag{1}$$

$$R_{SCC} = e^{-\lambda_{SCC}\, t} \tag{2}$$

$$R_{PV} = e^{-\lambda_{P}\, t} \tag{3}$$

$$R_{BAT} = e^{-\lambda_{B}\, t} \tag{4}$$

Reliability for the system R_S is defined by equation

$$R_S = e^{-\lambda_{INV}\, t}\, e^{-\lambda_{SCC}\, t}\left[1 - \left(1 - e^{-\lambda_P\, t}\right)\left(1 - e^{-\lambda_B\, t}\right)\right] \tag{5}$$

$$R_S = e^{-(\lambda_{INV}+\lambda_{SCC}+\lambda_P)\, t} + e^{-(\lambda_{INV}+\lambda_{SCC}+\lambda_B)\, t} - e^{-(\lambda_{INV}+\lambda_{SCC}+\lambda_P+\lambda_B)\, t} \tag{6}$$

Expected lifetime of the system when reliability from time t = 0 to infinity is defined by

$$\theta = \int_0^\infty R_S \, dt \tag{7}$$

$$\theta = \frac{1}{\lambda_{INV}+\lambda_{SCC}+\lambda_{PV}} + \frac{1}{\lambda_{INV}+\lambda_{SCC}+\lambda_{B}} - \frac{1}{\lambda_{INV}+\lambda_{SCC}+\lambda_{PV}+\lambda_{B}} \tag{8}$$

2.1.2 State system of an isolated microgrid in island

The isolated microgrids also can be modeled by the state systems. Vector state X represents the state variable of the components PV array, battery, solar charge controller, and inverter, respectively. System state function φ_j represents the system as a working or failed state.

Table 1 The simplified system state of an isolated microgrid.

Vector X	**System States** S_j	**System state function** φ_j	**System Characteristics**
(1, 1, 1, 1)	S0	1	1 PV and 1 B OK, 1 INV OK, 1 SCC OK, System OK
(1, 0, 1, 1)	S1P	1	1 PV OK, 1 INV OK, 1 SCC OK, System OK
(0, 1, 1, 1)	S1B	1	1 B OK, 1 INV OK, 1 SCC OK, System OK
(0, 0, 0, 0)	S2	0	1 INV or 1 SCC Fails, System Fails

2.1.3 Isolated microgrid without repaired components

The model is assumed when the microgrid is deployed without additional spare parts or repairing. In this model, the system transits to an absorbing state and resides permanently in this failed state. The transition factor is failure rate λ for each component, such as solar PV (λ_P), battery (λ_B), inverter (λ_{INV}), and solar charge controller (λ_{SCC}). Based on Table 1, the state diagram of an isolated microgrid is shown in Figure 4.

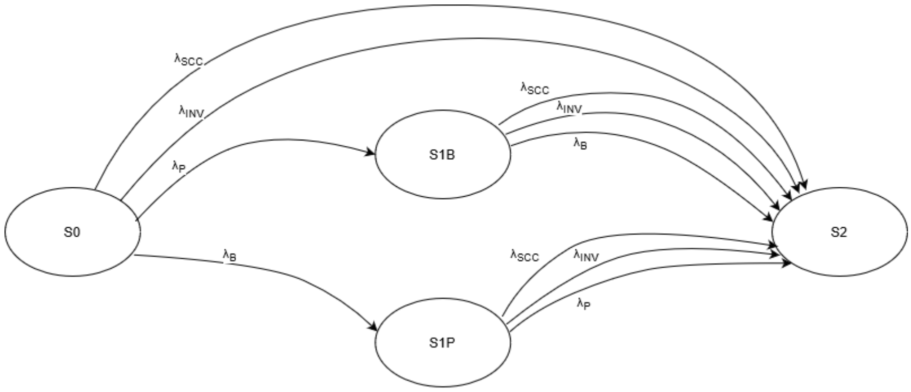

Figure 4 State diagram of system isolated microgrid

By Figure 4, the equation of state diagram in matrix form is

$$\begin{bmatrix} \dot{P_0} \\ \dot{P_{1B}} \\ \dot{P_{1P}} \\ \dot{P_2} \end{bmatrix} = [A] \begin{bmatrix} P_0 \\ P_{1B} \\ P_{1P} \\ P_2 \end{bmatrix} \tag{9}$$

Where

$$[A] = \begin{bmatrix} -(\lambda_{INV} + \lambda_{SCC} + \lambda_P + \lambda_B) & 0 & 0 & 0 \\ \lambda_P & -(\lambda_{INV} + \lambda_{SCC} + \lambda_B) & 0 & 0 \\ \lambda_B & 0 & -(\lambda_{INV} + \lambda_{SCC} + \lambda_P) & 0 \\ (\lambda_{INV} + \lambda_{SCC}) & (\lambda_{INV} + \lambda_{SCC} + \lambda_B) & (\lambda_{INV} + \lambda_{SCC} + \lambda_P) & 0 \end{bmatrix}$$

And the probability of the initial state P_0 (t=0) = 1 and other probabilities $P_{j\neq 0}$ (t=0) = 0.

Reliability of the system R_S is obtained after solving Eq. (9) is

$$R_S = P_0 + P_{1B} + P_{1P} \tag{10}$$

For t infinite, then the expected lifetime of the system can be calculated by

$$\theta = \int_0^\infty R_S \, dt \tag{11}$$

2.2 Isolated microgrid with repaired battery

In the condition that the isolated microgrid has trained personal and spare part of the battery to replace is available, the isolated microgrid can be modeled in Figure 5. In this model, there is a repair rate μ_B for repairing the battery when the battery fails.

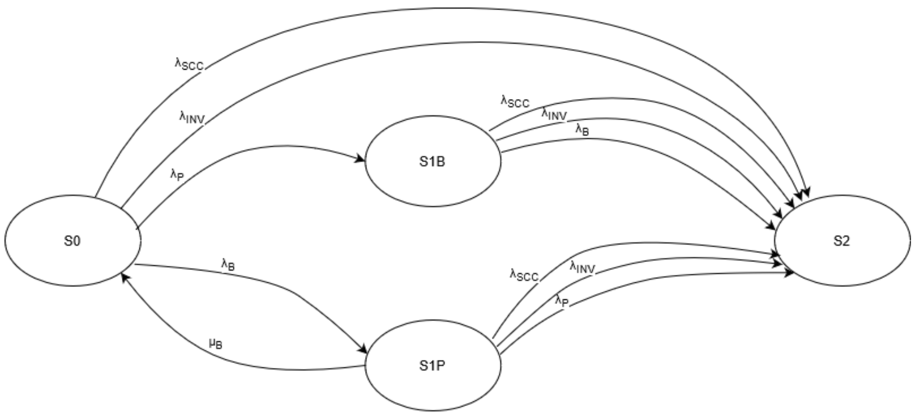

Figure 5 State diagram of system isolated microgrid with repaired battery

By Figure 5., the equation of the state diagram is following

$$\begin{bmatrix} \dot{P_0} \\ \dot{P_{1B}} \\ \dot{P_{1P}} \\ \dot{P_2} \end{bmatrix} = [A] \begin{bmatrix} P_0 \\ P_{1B} \\ P_{1P} \\ P_2 \end{bmatrix} \tag{12}$$

Where

$$[A] = \begin{bmatrix} -(\lambda_{INV} + \lambda_{SCC} + \lambda_P + \lambda_B) & 0 & \mu_B & 0 \\ \lambda_P & -(\lambda_{INV} + \lambda_{SCC} + \lambda_B) & 0 & 0 \\ \lambda_B & 0 & -(\lambda_{INV} + \lambda_{SCC} + \lambda_P + \mu_B) & 0 \\ (\lambda_{INV} + \lambda_{SCC}) & (\lambda_{INV} + \lambda_{SCC} + \lambda_B) & (\lambda_{INV} + \lambda_{SCC} + \lambda_P) & 0 \end{bmatrix}$$

And the probability of the initial state P_0 (t=0) = 1 and other probabilities $P_{j\neq 0}$ (t=0) = 0.

Reliability of the system R_S is obtained after solving Eq. (12) is

$$R_S = P_0 + P_{1B} + P_{1P} \tag{13}$$

In this case, there are two types of expected lifetimes that are MTTFF (Mean Time To First Failure) and MTBF (Mean Time Before Failure). MTTFF is the mean time that passes between commissioning and the first failure. The initial state is S_0 and the probability of the initial state P_0 (t = 0) = 1 and other probabilities $P_{j\neq0}$ (t = 0) = 0. The final state is S_2 and is an absorbing state.

$$MTTFF = \int_0^{\infty} R_S \, dt \tag{14}$$

The MTBF is calculated similarly. If the system is repaired after a failure, the initial state is S_{1P}, and the probability P_{1P} (t = 0) = 1.

$$MTBF = \int_0^{\infty} R_S \, dt \tag{15}$$

2.3 Isolated microgrid with the repair of all components

When the isolated microgrid is operated by the utility, the spare parts of all components are available continuously, and the personnel is trained and available to repair the failed components. The model of this case is shown in Figure 6, with the repair rate of all components is repair rate solar PV (μ_P), battery (μ_B), solar charge controller (μ_{SCC}), and inverter (μ_{INV}).

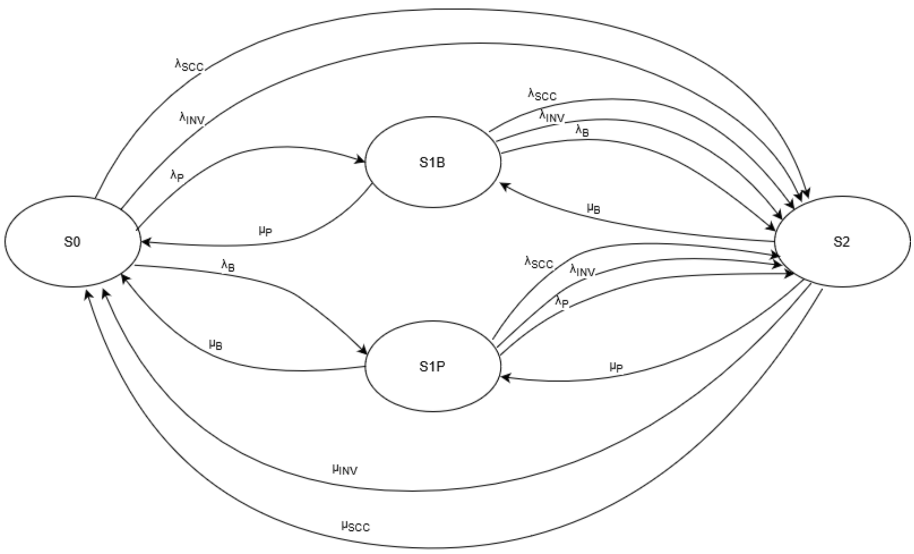

Figure 6 State diagram of system isolated microgrid with the repair of all components

By Figure 6, the equation of the state diagram is following

$$\begin{bmatrix} \dot{P_0} \\ \dot{P_{1B}} \\ \dot{P_{1P}} \\ \dot{P_2} \end{bmatrix} = [A] \begin{bmatrix} P_0 \\ P_{1B} \\ P_{1P} \\ P_2 \end{bmatrix} \tag{16}$$

Where

$$[A] = \begin{bmatrix} -(\lambda_{INV} + \lambda_{SCC} + \lambda_P + \lambda_B) & \mu_P & \mu_B & (\mu_{INV} + \mu_{SCC}) \\ \lambda_P & -(\lambda_{INV} + \lambda_{SCC} + \lambda_B + \mu_P) & 0 & \mu_B \\ \lambda_B & 0 & -(\lambda_{INV} + \lambda_{SCC} + \lambda_P + \mu_B) & \mu_P \\ (\lambda_{INV} + \lambda_{SCC}) & (\lambda_{INV} + \lambda_{SCC} + \lambda_B) & (\lambda_{INV} + \lambda_{SCC} + \lambda_P) & (\mu_{INV} + \mu_{SCC} + \mu_P + \mu_B) \end{bmatrix}$$

And the probability of the initial state P_0 (t=0) = 1 and other probabilities $P_{j\neq 0}$ (t=0) = 0.

Reliability of the system R_S is obtained after solving Eq. (16) is

$$R_S = P_0 + P_{1B} + P_{1P} \tag{17}$$

With a repairable system, the system will balance between the working and failed states in the long run, and the times to reside in either type of state will be infinite. The average time of functioning and failure will both become infinite, but it is possible to determine the availability A. The initial state is taken as S_0 and the availability A (t = 0) = 1 is equal to the probability of the initial state P_0 (t = 0) = 1. The system will find an equilibrium between the probabilities and their derivatives becoming zero. To solve the equations, one more condition is required is that the sum of all probabilities must be equal to 1 at all times.

$$A = \sum_{i,working} P_i(t) = P_0 + P_{1B} + P_{1P} \tag{18}$$

3 Results

In this study, reliability data of failure rates and repair rates of components uses existing literature. It assumed that the probability of distribution is independent and follows an exponential distribution. The mean of failure rates and repair rates of components from the literature [21] is shown in Table 2.

The reliability for the cases is calculated using MATLAB R2021a. The differential equation to solve the equation of the state diagram of the system is defined by

$$\dot{Y} = [A]\, Y \tag{17}$$

Where [A] is the matrix of the state diagram of the system.

Table 2 Mean of failure rates and repair rates of components [21]

Component	Failure rate, λ (10-6 failures per hour)	Repair rate, μ (repair per hour)	Expected life (year)
PV module	5.3058	0.0181	21.5
Battery system	12	0.0059	9.5
Inverter	27.9429	0.0288	4.1
Solar Charge Controller	6.4	0.0084	17.8

Table 3 Reliability of an isolated microgrid without repaired components

Method	Block diagram	State system	Error (ε)
Expected lifetime	θ = 27438.2148 hours	θ = 27438 hours	- 0.00078285%
Reliability	Rs = 0.37491453	Rs = 0.374915956	0.00038034%

Modeling of the system is validated, and the result shows the model is acceptable. In this case, high precision is achieved because all components are represented, and more the state system function is counted. The state system model is used to study the effect of repair for the component.

Table 4 Reliability and expected lifetime of an isolated microgrid

Case of reliability	Isolated microgrid without repaired components	Isolated microgrid with repaired battery	Isolated microgrid with the repaired of all components
Reliability Indicator	Rs	Rs	A
Expected lifetime	θ = 27438 hours	MTTFF = 28103 hours MTBF = 28084 hours	Infinite
Reliability	Rs (θ) = 0.3749	Rs (θ) = 0.3727	A = 0.9994

The reliability in Table 4 is the reliability at the end of expected life. Without repairing components or maintenance, the expected lifetime of the system depends on the smallest expected lifetime of the components. Maintenance to repair the failure battery improves the expected lifetime and reliability of the system where the system is working. The availability of the system is high due to continuous maintenance by the utility. The expected lifetime of the system becomes infinite, then the financial evaluation of the system is easier.

The reliability is calculated for the value of failure rates is increased two times and shown for one year, and the result is shown in Table 5. Sensitivity analysis shows that when the value of failure rates is increased two times, then the reliability and expected lifetime are more affected by failure rates of inverter and solar charge controller than failure rates of battery and solar PV. It is due to the topology of the system where the inverter and solar charge controller is connected serially. The availability of the system does not change significantly due to the equilibrium of the system. It follows a component that has the smallest value of the failure rates. The reliability and the expected lifetime are more sensitive to variation of failure rates component that has high failure rates; in this case, it is the inverter.

Table 5 Sensitivity of failure rates of components

Case of reliability	Isolated microgrid without repaired components	Isolated microgrid with repaired battery	Isolated microgrid with the repair of all components
Reliability Indicator	Rs	Rs	A
Normal (λ_B)	θ = 27438 hours Rs (1 year) = 0.7368	MTTFF = 28103 hours MTBF = 28084 hours Rs (1 year) = 0.7384	Infinite A = 0.9994
Failure rate battery (2 λ_B)	θ = 26650 hours Rs (1 year) = 0.7338	MTTFF = 27506 hours MTBF = 27491 hours Rs (1 year) = 0.7367	A = 0.9994
Failure rate PV module (2 λ_P)	θ = 26265 hours Rs (1 year) = 0.7336	MTTFF = 27328 hours MTBF = 27290 hours Rs (1 year) = 0.7336	A = 0.9994
Failure rate Inverter (2 λ_{INV})	θ = 15692 hours Rs (1 year) = 0.5769	MTTFF = 15849 hours MTBF = 15837 hours Rs (1 year) = 0.5781	A = 0.9990
Failure rate SCC (2 λ_{SCC})	θ = 23449 hours Rs (1 year) = 0.6967	MTTFF = 23896 hours MTBF = 23879 hours Rs (1 year) = 0.6982	A = 0.9993

The reliability is calculated for the value of repair rates is increased two times and shown for one year, and the result is shown in Table 6. Sensitivity analysis shows that when the value of repair rates is increased two times, then the reliability and expected lifetime increase.

In this case, the increased repair rates of battery more affect to MTBF value than MTTFF, where it increases 0.05% and 0.01%, respectively. The availability increases concerning the increasing value of repair rates, where it is around 0.01% for double value repair rates of battery and solar charge controller, and 0.02% for double value repair rates of solar PV and inverter.

Table 6 Sensitivity of repair rates of components

Case of reliability	**Isolated microgrid with repaired battery**	**Isolated microgrid with the repair of all components**
Reliability Indicator	Rs	A
Normal (μ_B)	MTTFF = 28103 hours MTBF = 28084 hours Rs (1 year) = 0.7384	A = 0.9994
Repair rate battery (2 μ_B)	MTTFF = 28106 hours MTBF = 28097 hours Rs (1 year) = 0.7384	A = 0.9995
Repair rate PV module (2 μ_P)	N/A	A = 0.9996
Repair rate Inverter (2 μ_{INV})	N/A	A = 0.9996
Repair rate SCC (2 μ_{SCC})	N/A	A = 0.9995

4 Conclusion

This paper describes the modeling reliability of an isolated microgrid based on solar PV, battery, solar charge controller, and inverter. It presents the reliability of an isolated microgrid using state-space analysis with the Markov process. An isolated microgrid is modeled for 3 cases, where the first case does not have maintenance, the second case only has repaired for battery, and the third case has full maintenance by the utility. Without repairing components or maintenance, the system has the expected lifetime of 3 years that depends on the smallest expected lifetime of the components, in this case, is an inverter of 4 years. Maintenance to repair the failure battery improves the expected lifetime and reliability of the system where the system is working. Expected lifetime increases around 2% compared to without repairing components. The reliability in the table is 37.27% in the third year or at the end of expected life. In the third case, the availability of the system is 99.94% which is high due to continuous maintenance by the utility. The expected lifetime of the system becomes infinite, and then the financial evaluation of the system is easier to be evaluated.

Sensitivity analysis is conducted with the variation of failure rates and repair rates for one year. The result of sensitivity analysis shows that the reliability and expected lifetimes are affected by topology and the value of failure rates. It is more sensitive to variation of failure rates component that has high failure rates; in this case, it is the inverter. Variation of repair rates affects MTBF and MTTFF; in the case model of repaired battery, it increases 0.05% and 0.01%, respectively. The availability increases 0.01% and 0.02% for the double value of repair rates.

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