



Reliability Study of Stand-alone Hybrid Renewable Energy Microgrids

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Abstract

This paper proposed new indices for investigating the reliability of the microgrid at different levels. The microgrid used has been developed in DigSILENT software and is comprised of wind, solar, battery storage and a diesel generator. The software was used to observe the effect of system demand and the failure rate of each component at three indices levels. Different simulations had shown that an increase in the system demand affects average energy not supplied, EIC, and average customer curtailment index. Also, at load point, LPIC and load point energy not supply among others are sensitive to system demand. This work proposes a new approach to study the effect of network structure on the reliability of a microgrid. The proposed method employs the prioritization of component importance on microgrid configuration. The results obtained show that the contribution of components to the system's reliability depends on the network structure. This could be used in identifying direction, priority, and upgrading and suggests the most efficient way to operate and maintain a microgrid.

Keywords Microgrid · Renewable energy · Solar · Wind · Battery storage and diesel generator

1 Introduction

Reliability is defined as the probability that a system, product or service operates properly for a specific period of time under operating conditions without failures. Irrespective of the system configuration, the reliability of the

system is the most important factor for system planners. However, the success of any design could be attributed to the success of the system when it operates for a longer period.

In recent times, investigations of the relationship between the system reliability and operating conditions on the reliability of microgrid have been considered in Xu

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et al. (2014). In Ghahderijani et al. (2012a), the reliability of microgrid has been analysed considering load and generation taking into account conventional and renewable resources using Monte Carlo simulation. Model for the analysis of microgrid consisting of wind and PV system has been developed in Huang et al. (2011) where operation modes and different types of loads were considered using the minimum path method. The effect of the repair rate on the reliability of microgrid has been studied in Theristis and Papazoglou (2014). Other efforts include the investigation of the effects of the distributed generation on the reliability of microgrid (Kennedy 2009) while (Bae and Kim 2008) evaluates the reliability of microgrid considering the customers' interruptions cost (Abdulkarim and Adediran 2011).

The effects of size and location factors on the reliability of wind turbine generator have been investigated in Xu and Islam (2006). Similar analysis has been carried out by adding a storage system in the model (Bhuiyan and Yazdani 2010). In Liu and Islam (2006), Xu et al. (2008), discrete wind speed frame analysis was proposed. A multi-state model was developed in Liang et al. (2009) to study the reliability of power system including wind generator. Also, capacity limitations and transmission line forced outage rates were incorporated in the reliability analysis in Jaeseok et al. (2010a). Reliability evaluation of power system, including wind turbine generator on grid-connected mode, can be found in Cho et al. (2011), Park et al. (2012). In Gao and Wang (2010) the effects of rated capacity, charging and discharging behaviour of storage system on the microgrid were investigated. A technique that increased the reliability of microgrid by minimizing the number of unsupplied loads and switch for each fault is proposed in Calderaro et al. (2012). Recently, a stochastic evaluation method is proposed for the reliability of microgrid based on the value of loss of load (Aghaei et al. 2016). Another method to detect the location of renewable energy generators and exact location of faults on microgrid is developed in Heidari et al. (2014).

Reliability studies of the renewable energy system consisting of solar energy conversion system in a stand-alone mode are reported in Jeongje (2009), Jaeseok et al. (2010b). In Jeongje (2009), a multi-stage model of a solar conversion model has been developed, while another method for the reliability of solar energy conversion system was developed by Jaeseok et al. (2010b). Evaluations of reliability of hybrid renewable energy were carried out in Park et al. (2010), Aien et al. (2013). In Park et al. (2010), a multi-state model for the reliability analysis of the WECS and SECS has been developed. A multi-state technique at hierarchical level II has been reported in Ghaedi et al. (2013). Revised capacity outage probability table was considered in Aien et al. (2013). Recent studies

in Kekezoglu (2013) analysed the reliability of hybrid microgrid installed in Davutpasa University Campus. Applications of Monte Carlo simulation have been presented in Ghahderijani et al. (2012a), Alkuhayli et al. (2012). Authors in Ghahderijani et al. (2012a) analysed the reliability of microgrid considering load and generation. Reference Ghahderijani et al. (2012b) studies the reliability of stand-alone microgrids using loss of load expectation (LOLE) and loss of load factor (LOLF) as reliability indices. A similar study was carried out in Ghahderijani et al. (2012b) with a microgrid having different configurations and addition of solid oxide fuel cell (SOFC). Different simulations on the cost and reliability analysis of PV and wind microgrid have been carried out in Karki and Billinton (2001). Investigation in Kishore and Fernandez (2011) proposed a method known as well-being analysis that combined deterministic and probabilistic technique. The effects of implementing PV, WT on the reliability of Roy Billinton Test System (RBTs) bus 2 have been analysed in Alkuhayli et al. (2012).

Authors in Salehizadeh et al. (2014a) proposed a technique for managing security and carbon emission reduction in power system using a multi-objective optimization framework, outage of transmission components and the degree of severity (DOS). In addition, in Salehizadeh et al. (2014b), a procedure based on multi-attribute approach has been proposed for the determination of power generation plan (PGP) by considering transmission congestion management (TCM) attributes and different possible scenarios. A method is proposed in Salehizadeh et al. (2015) that could assist in decision making for system operators to choose the best strategy by considering congestion and environmental attributes in power system with renewable energy resources. A procedure to study the effects of weather on the availability of hybrid microgrid has been investigated in Abdulkarim et al. (2016); however, the proposed techniques may not provide a realistic ranking of the component contribution to the power system consisting of renewable energy resources and battery storage.

The literature review has shown that most of the research efforts on the reliability of microgrids were based on EENS, LOLF and LOLE (Ghahderijani et al. 2012a; Abdulkarim et al. 2016). The reliability of a stand-alone microgrid is usually evaluated from the viewpoint of demand and supply (Xu et al. 2014). Until recently, less consideration if any at all has been paid to other factors that may affect the reliability of stand-alone microgrid which includes reliability of non-electric components, number of connected customers (loads), the network structure and the type of fault. However, in this paper, it is assumed that the reliability analysis of microgrid is beyond the load and demand mismatch. Therefore, the reliability of the microgrid is analysed at three levels including load points,

busbar and system levels. In order to analyse the reliability of microgrid at these levels, indices at each level were defined. This makes it possible to define new indices that have not previously been used in the reliability analysis of a microgrid. In addition, this presentation enables the analysis of microgrid reliability via different configurations. Different microgrid configurations analysed include AC, DC and AC–DC microgrids. The study also analysed the reliability measures of components importance for different microgrid configurations. Furthermore, the effect of component on the microgrid reliability is also investigated. In order to achieve these, the reliability model of each unit is obtained using the reliability block diagram. This presentation enables us to determine which components are more important to the microgrids reliability improvement or more critical to system failure.

2 Definition of the Indices

The indices used are defined according to the power factory user manual (DIgSILENT 2014). Hence, the following indices are used in this work:

C_i	The number of customers supplied by load point i
A_i	The number affected customers for an interruption at load point i
F_{rk}	The frequency of occurrence of contingency k
pr_k	The probability of occurrence of contingency k
L_m	The total connected kVA interrupted, for each interruption event, m
r_m	Duration of each interruption event, m
L_T	The total connected kVA supplied,
P_{Ci}	Contracted active power at load point i
WECS	Wind energy conversion system
SECS	Solar energy conversion system
MV_X	Medium voltage of X,
LV_X	Low voltage of X where X is WECS, SECS, diesel generator, battery storage system
SAIFI	System average interruption frequency index
CAIFI	Customer average interruption frequency
ASIFI	Average system interruption frequency
SAIDI	System average interruption duration index
CAIDI	Customer average interruption duration
ASIDI	Average system interruption duration index
ASAI	Average service availability index

ENS	Energy not supplied
ASUI	Average service availability index
ACCI	Average customer curtailment index
LPENS	Load point energy not supply
LPES	Load point energy shed
ACCI	Average customer curtailment index
AENS	Average energy not supplied
ACCI	Average customer curtailment index
AID	Interruption durations
AIF	Yearly interruption frequency
AIT	Yearly interruption time
AID	Average interruption duration
ACIF	Average customer interruption frequency
ACIT	Average customer interruption time
TCIT	Total customer interruption time
TCIF	Total customer interruption frequency
I_i^B	Birnbaum importance of components i
R_s	System reliability at time t
$R_i(t)$	Reliability of components i at time t
CI	Criticality importance
NRAW _{i}	Network reliability achievement worth
NRRW _{i}	Network reliability reduction worth
$R_s(t; R_i(t) = 0)$	is the system reliability with the component reliability $i = 0$
$R_i(t)$	is the component reliability
λ_i	Failure rate of component i

3 Definition of Terms

- System average interruption frequency index (SAIFI) is defined as the number of times an average customer experienced outage for a period of 1 year (Alkuhayli et al. 2012).

$$SAIFI = \frac{\sum ACIF_i \cdot C_i}{\sum C_i} \quad (1)$$

- Customer average interruption frequency (CAIFI) is the mean frequency of sustained interruptions for those customers experiencing sustained interruption per annum. Mathematically it can be defined as

$$CAIFI = \frac{\sum ACIT_i \cdot C_i}{\sum A_i} \quad (2)$$

- Average system interruption frequency index (ASIFI) is used to measure the performance in the areas that supply relatively few customers with large concentration of load. The expression for the determination of this distribution is given by

$$\text{ASIFI} = \frac{\sum L_m}{L_T} \quad (3)$$

- The average duration a customer experienced interruption during the period of 1 year is called SAIDI, and is usually measured in customer minute of customer average hours of interruptions, and is mathematically expressed in Eq. (4)

$$\text{SAIDI} = \frac{\sum \text{ACIT}_i \cdot C_i}{\sum C_i} \quad (4)$$

- Customer average interruption duration index (CAIDI) is a mean time to restore service and it is defined as

$$\text{CAIDI} = \frac{\text{SAIDI}}{\text{SAIFI}} \quad (5)$$

- Average system interruption duration index (ASIDI) is equivalent to SAIDI but based on load rather than customer; mathematical expression of the index is given by

$$\text{ASIDI} = \frac{\sum (r_m - L_m)}{L_T} \quad (6)$$

- Average service availability index (ASUI) defines the probability of all load supplied

$$\text{ASUI} = \frac{\sum \text{ACIT}_i \cdot C_i}{8760 \cdot \sum C_i} \quad (7)$$

- Average service availability index (ASAI) defines the fraction of time a customer is connected during the calculation period.

$$\text{ASAI} = 1 - \text{ASUI} \quad (8)$$

- Load point energy not supply (LPENS) and load point energy shed (LPES), the two indices, are defined in Eqs. (9) and (10), respectively,

$$\text{LPENS}_i = \text{ACIT}_i \cdot (\text{Pd}_i + \text{Ps}_i) \quad (9)$$

$$\text{LPES}_i = \text{ACIT}_i \cdot \text{Ps}_i \quad (10)$$

where Pd_i and Ps_i are the weighted average amount of power disconnected and weighted average amount of power shed at load point i , respectively.

- Energy not supplied in (MWh/a) is the total amount of energy on average not delivered to the system loads

$$\text{ENS} = \sum \text{LPENS}_i \quad (11)$$

- System energy shed (SES) in (MWh/a) is the amount of energy on average to be shed in the system

$$\text{SES} = \sum \text{LPES}_i \quad (12)$$

- Average energy not supplied (AENS) in (MWh/Ca) determines the average amount of energy not supplied, for all customers,

$$\text{AENS} = \frac{\text{ENS}}{\sum C_i} \quad (13)$$

- Average customer curtailment index (ACCI) in (MWh) is the average energy not supplied for the affected customers connected to the grid and is defined as

$$\text{ACCI} = \frac{\text{ENS}}{\sum A_i} \quad (14)$$

In addition, the paper proposed to investigate the effects of other indices at busbar point; this includes average interruption durations (AID) (h), yearly interruption frequency (AIF) (1/y) and yearly interruption time (AIT) in (h/y).

4 Application of the Proposed Procedure

The procedure for the reliability assessment used in this paper is described in the flowchart shown in Fig. 1. The diagram is adopted from the DIgSILENT operation manual (DIgSILENT 2014). Also, the microgrid and the loads used in the reliability study are shown in Figs. 2 and 3, respectively. The model is developed by using DIgSILENT simulation software, and the input data are presented in Table 1. Based on the proposed procedure, the reliability analysis is carried out in three stages. The first stage is the development of the microgrid in a simulation environment, followed by the network set up for reliability analysis, while the systems are simulated under different operating conditions at the last stage. The microgrid is configured according to Table 1, and different models are defined based on the customer interruption function as shown in Table 2 (Casteren 2003). Also, the failure rate and the case studies considered are shown in Tables 3 and 4, respectively.

5 Effects of the System Demand

In this section, the reliability of the system is analysed at different levels by increasing the system demand. Table 4 shows the details of the cases considered in the study. In this analysis, the base case is the system configuration obtained from the base design. Cases II and III represent an increase in system demand by 25 and 50%, respectively. The proposed microgrid is assumed to comprise a cluster of load and distributed generation. It is assumed that the system is configured to include 8 different loads. Each load represents a cluster of a number of connected customers. This presentation enables the effects of the load demand on the reliability indices of microgrid at all levels. The results of the analysis are presented for all the indices defined at system demand levels.

Fig. 1 Procedure used in the reliability assessment of microgrid

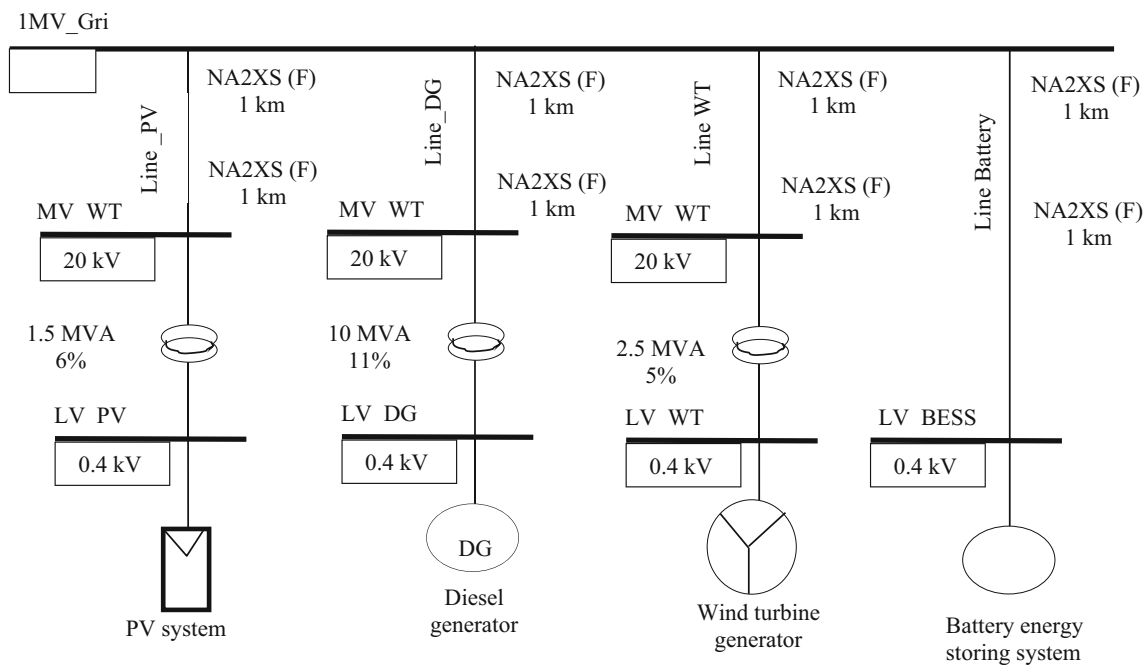
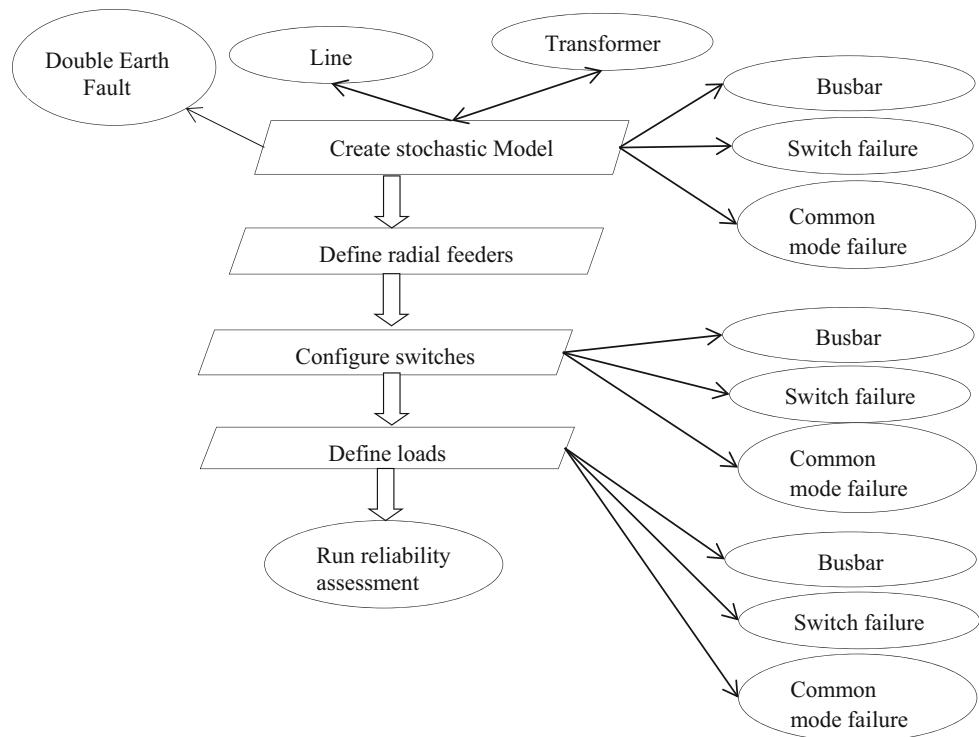


Fig. 2 Line diagram of the microgrid

5.1 System Summary Indices

Table 5 shows the result of various simulations on the effects of the load demand on the three cases of analysis. Some of the system indices remain constant at 25 and 50% increase in the system demand. The reliability indices that

show a significant variation with system demand are the ENS, AENS, EIC and ACCI. It can be observed that increasing the system demand by 25 and 50% increases the indices by 20 and 33.33%, respectively. Therefore, the relationship is linear by a factor less than the corresponding load factor.

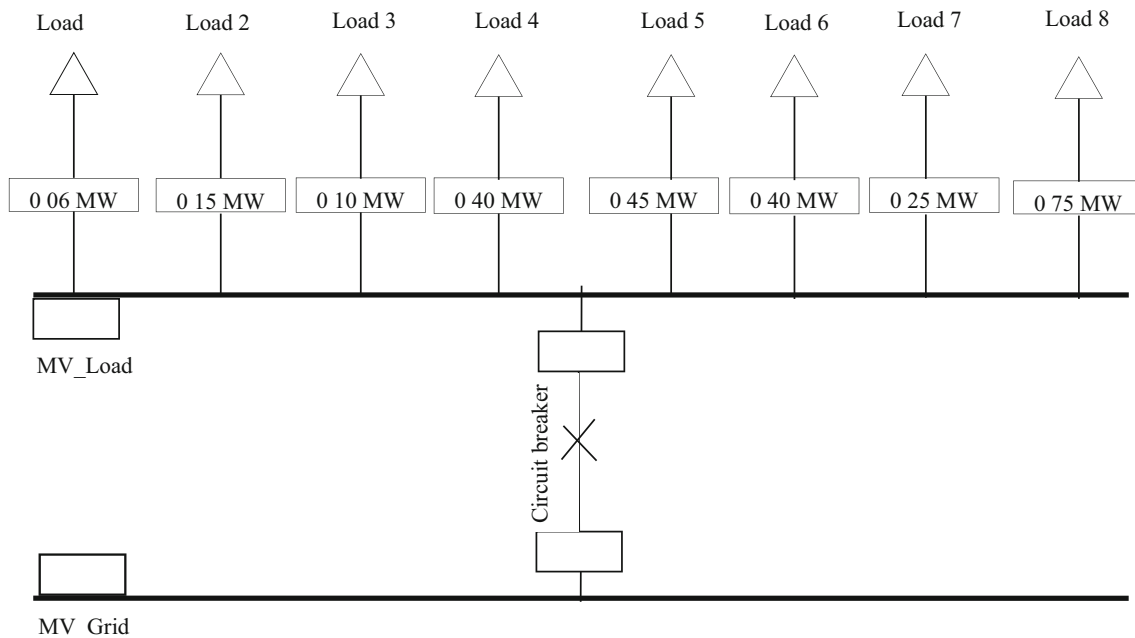


Fig. 3 Loads connected to the microgrid

Table 1 System configuration

	Rated power	Rating
SECS		0.80 kW
WECS		335.75 kW
Diesel generator		162.35 kW
Battery storage		89.85 kWh

Table 2 Interruption cost

Type of load	Agriculture	Commercial	Industry	Residential
\$/kW	0.157	5.73	6.79	0.293

Table 3 Failure rates of different components

Buses name	Failure frequency (1/a)
MV_Load	0.0035
LV_PV	0.002
LV-WT	0.002
MV_PV	0.0025
MV_WT	0.0025
MV_BECS	0.0025
MV_Grid	0.0035
MV_CoGen	0.0025
LV_CoGen	0.002
Cable (1/a*km)	0.01
Transformer	0.02

5.2 Load Interruption Indices

This section presents the results of the influence of load demand on the reliability at the load point. In this case, the load demand at each customer end is configured according to the scenarios presented in Table 3. The results shown in Table 6 are categorized into two parts. Part one is the indices that are constant irrespective of the system demand; these include AID, ACIF and ACIT, and the second part shows that TCIT and TCIF are sensitive to the system demand. Customers that have the same load classification even with different ratings will have the same TCIT and CIF indices. Hence, the determinant factor of these indices is the customer damage function defined in the tariff model. Also, the two indices remain constant irrespective

of the system demand. On the other hand, AID, ACIF and ACIT remain constant throughout the system demand. Therefore, neglecting the influence of system demand could lead to unforeseen system failure or decrease system reliability, hence leading to corresponding decrease in system benefit.

Other factors that depend on the system demand include LPENS and LPIC. The result of the analyses is shown in Figs. 4, 5. Figure 4 shows that the base case has the least LPENS value followed by the cases I and II in that order. Also, as the system demand increases, the index also increases. Similar trends are also observed in the case of LPIC as shown in Fig. 5.

Table 4 System configuration

Load	System demand (kW)	No. of loads	25% Increased	50% Increased
Load 1	5	10	6.25	7.5
Load 2	15	10	18.75	22.5
Load 3	5	20	6.25	7.5
Load 5	20	20	25	30
Load 5	55	10	56.25	67.5
Load 6	50	10	50	60
Load 7	25	10	31.25	37.5
Load 8	50	15	62.5	75
Total	205	105	256.25	307.5

Table 5 System indices

Indices	Base case	Case I	Case II	Units
SAIFI	52.15	52.15	52.15	1/Ca
CAIFI	52.15	52.15	52.15	1/Ca
SAIDI	529.87	529.87	529.87	h/Ca
CAIDI	10.16	10.16	10.16	h
ASAI	0.94	0.94	0.94	p.u
ASUI	0.06	0.06	0.06	p.u
ENS	585.58	731.85	878.22	MWh/a
AENS	5.58	6.97	8.37	MWh/Ca
ACCI	5.90	6.12	7.35	MWh/Ca
EIC	2.63	3.29	3.95	M\$/a
IEAR	5.60	5.60	5.60	\$/kWh
ASIFI	52.15	52.15	52.15	1/a
ASIDI	529.87	529.87	529.87	h/a

Table 6 Load indices

Load name	TCIT Ch/a	TCIF C/a	AID H	ACIF 1/a	ACIT h/a
Load1	5298.70	521.53	10.16	52.15	529.87
Load2	5298.70	521.53	10.16	52.15	529.87
Load3	10,597.51	1052.86	10.16	52.15	529.87
Load5	10,597.51	1052.86	10.16	52.15	529.87
Load5	5298.70	521.53	10.16	52.15	529.87
Load6	5298.70	521.53	10.16	52.15	529.87
Load7	5298.70	521.53	10.16	52.15	529.87
Load8	7958.06	782.15	10.16	52.15	529.87

5.3 Busbar Indices

The buses indices investigations are also presented in this section. Table 7 shows the result of the simulation. It can be seen that all the indices are affected by the increase in system demand. The results represent the busbars reliability indices, including AIT, AIF and AID. These busbars

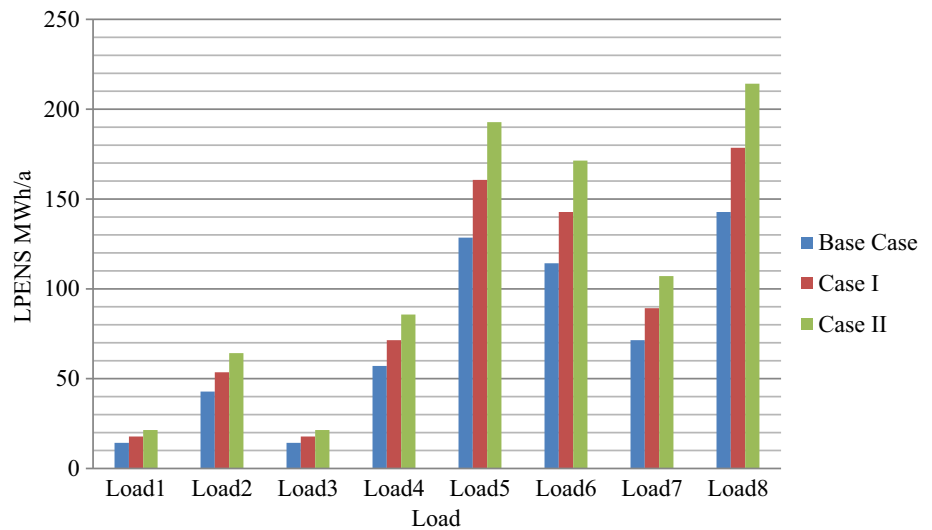
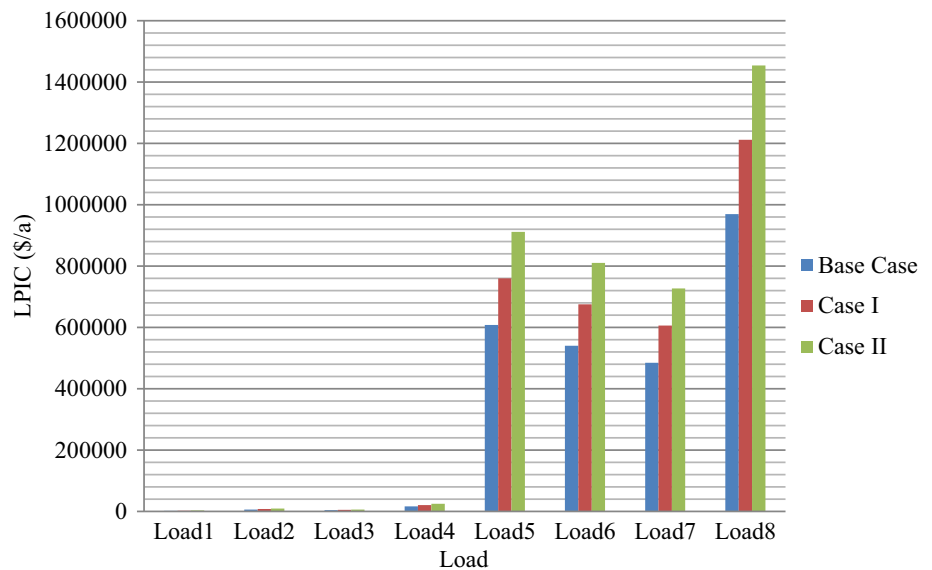
indices are sensitive to the system demand. According to the result, the busbar with the highest AIT index is MV_Load followed by LV_PV_OF, LV-WT, MV_PV_OF, MV_WT, MV_BESS, MV_Grid, MV_Co-Gen and LV_CoGen, respectively. A similar trend is observed in the case of AIF index. MV_Co Gen busbar has the highest AID followed by LV-WT, LV_PV_OF, MV_Grid, MV_BESS, MV_WT, MV_PV_OF, LV_CoGen and MV_Load, respectively. It can be observed that diesel generator busbar is the most reliable due to the least interruption indices.

6 Contributions of Components to the Reliability of the Microgrid

In this section, the contribution of the components to the reliability of a microgrid is investigated. In order to achieve this aim, the reliability block diagram (RBD) technique is used to model the reliability of the microgrid. The advantage of modelling the microgrid using this technique is that other behaviours of the system can also be investigated. RBD is a graphical method of representing components that make up a particular system, showing how they are connected. In the reliability analyses of electrical systems such as microgrid, single line diagram could be used. The components that make up the system are represented as blocks on the reliability block diagram. Therefore, when a constant failure rate is assumed, the reliability of the system follows an exponential distribution in Eq. (15) (Abdulkarim et al. 2011),

$$R = e^{-\lambda t}. \quad (15)$$

The blocks are connected in the same way as the flow of electric power, and the reliability of the microgrid is obtained by using RBD theorem. From the RBD point of view, the components are said to be connected in series if they all must work for the successful operation of the system or when the failure of one component results in system failure. For series connectivity, the reliability

Fig. 4 Load indices (LPENS)**Fig. 5** Load indices (LPIC)**Table 7** Busbar indices for the three cases

Buses name	AIT h/a	AIF 1/a	AID H
MV_Load	529.87	52.15	10.16
LV_PV_OF	18.35	0.23	80.65
LV-WT	17.65	0.20	87.18
MV_PV_OF	11.32	0.20	57.91
MV_WT	10.63	0.17	62.32
MV_BEES	10.35	0.16	65.22
MV_Grid	9.87	0.15	69.02
MV_CoGen	7.78	0.06	130.81
LV_CoGen	0.17	0.01	15.00

function can be given as in Eq. (16) (Kanabar and Sidhu 2009) (Fig. 6).

$$R_s(t) = R_1(t)R_2(t) = e^{-(\lambda_1 + \lambda_2)t} \quad (16)$$

On the other hand, when two blocks are connected in parallel with redundancy, 1 out of 2 is necessary for the successful operation of the system. The system will be successful if only one of the blocks is working, and the system failure occurs if all the components fail. The system reliability block diagram is shown in Fig. 7, and the reliability of the system as a function of time $R_s(t)$ is defined in Eq. (17) (Abdulkarim and Adediran 2011).

$$R_s(t) = R_1(t) + R_2(t) - R_1(t)R_2(t) \\ = e^{\lambda_1 t} + e^{\lambda_2 t} - e^{-(\lambda_1 + \lambda_2)t} \quad (17)$$

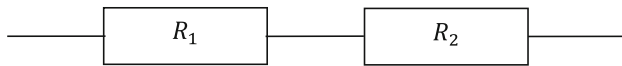


Fig. 6 Series system with two components

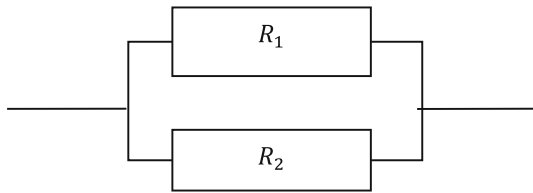


Fig. 7 Parallel systems with two components

7 Reliability Importance Measures

Reliability measures could be used to identify component within a particular system that influences the behaviour of the system. The most important aspect of the matrix is the ability to assess the contribution of a component, system or model for the system overall behaviour. Components importance analyses are carried out in the power industry to provide the management with the adequate knowledge for reliable, safe and efficient operation of the system under consideration. Another application of the proposed component criticality or importance measure is the ability to monitor system reliability during operation; safety and reliability improvement can be inferred (Peng et al. 2012; Ramirez-Marquez and Coit 2005).

7.1 Barbiums Importance

Barbiums importance measure defines the maximum loss in system reliability when a particular component i transits from perfect functioning to the condition of certain failure. It is true that some components are more important than others in contributing to the system failure. This measure numerically ranks the contribution of individual component's contribution to the system failure or reliability (Peng et al. 2012; Ramirez-Marquez and Coit 2005). The mathematical expression is given in Eq. (18),

$$I_i^B(t) = \frac{\partial R_s(t)}{\partial R_i(t)} \quad (18)$$

where I_i^B Birnbahum importance of components i , R_s system reliability at time t , $R_i(t)$ reliability of components i at time $= t$.

7.2 Criticality Importance

Another measure of importance is an extension of Eq. (18) called the criticality importance (CI) measure. The measure is used to determine the probability that a component was

responsible for system failure at time t (Abdulkarim et al. 2011). This measure uses the components unreliability $F_i(t)$ and system unreliability $F_s(t)$ that are not considered in Eq. (18). The expression for the determination of CI is defined in Eq. (19).

$$I_i^{CI}(t) = I_i^B(t) \cdot \frac{F_i(t)}{F_s(t)} \quad (19)$$

From the definition, it can be observed that for component i being responsible for system failure before time t , i must be critical and then fail. This means if component i fails, then the system fails. On the other hand, when the component is repaired, the system starts functioning again. Due to the nature of this measure, it is suitable for defining priority maintenance in complex systems. The maintenance could be preventive, corrective or failure finding maintenance. In addition, two other measures are proposed in order to quantitatively evaluate the impacts of a particular component to the system reliability. These include network reliability achievement worth (NRAW) and network reliability reduction worth (NRRW).

7.3 Network Reliability Achievement Worth

The network reliability achievement worth is defined as the ratio of the actual system reliability if component i is always in perfect condition ($R_i(t) = 1$), to the actual system reliability. This measure is used to indicate the importance of maintaining the current level of component reliability for the system reliability (Vancells et al. 2013). It can be used to determine the reliability increases due to the components i that measures the maximum percentage increase in system reliability generated by a particular component (Ramirez-Marquez and Coit 2005),

$$\text{NRAW}_i = \frac{R_s(t; R_i(t) = 1)}{R_s(t)} \quad (20)$$

where $R_s(t; R_i(t) = 0)$ is the system reliability with the component reliability $i = 0$, $R_i(t)$ is the component reliability.

7.4 Network Reliability Reduction Worth

Network reliability reduction worth defines the ratio of current system reliability when component i is considered always failed ($R_i(t) = 0$) (Nolasco 2007). Similarly, NRRW defines an index for measuring the damage caused to the system reliability by a component i , and the mathematical relation is given by (Abdulkarim et al. 2015)

$$\text{NRRW}_i = \frac{R_s(t)}{R_s(t; R_i(t) = 0)} \quad (21)$$

7.5 Applications of the Proposed Method

In order to demonstrate the application of the proposed procedure in the design of microgrid, a standard low-voltage microgrid shown in Fig. 8 is used. The study is based on the assumption that the low-voltage microgrid is running in island mode for a period of time t . Therefore, reliability model for each load is developed. The reliability of the network does not consider the protection and control equipment; the inclusion of such component in the analyses will increase the complexity of the model. The parameters of the proposed microgrid can be found in Li et al. (2010), Papathanassiou et al. (2005). The microgrid consists of load points 1–8, WECS, SECS, storage system and a diesel generator. The reliability block diagram for load 1 is shown in Fig. 9. Equations (22)–(35) are derived using the reliability block diagram theorems.

$$R_1 = e^{-(\lambda_{PV} + \lambda_{INV} + \lambda_{L9})t} \quad (22)$$

$$R_2 = e^{-(\lambda_{DG} + \lambda_{L10})t} \quad (23)$$

$$R_3 = 1 - (1 - R_1)(1 - R_2) \quad (24)$$

$$R_5 = R_3 e^{-\lambda_{L8}t} \quad (25)$$

$$R_5 = e^{-(\lambda_{PV} + \lambda_{INV})t} \quad (26)$$

$$R_6 = e^{-(\lambda_{WT} + \lambda_{REC})t} \quad (27)$$

$$R_7 = 1 - (1 - R_6)(1 - R_5) \quad (28)$$

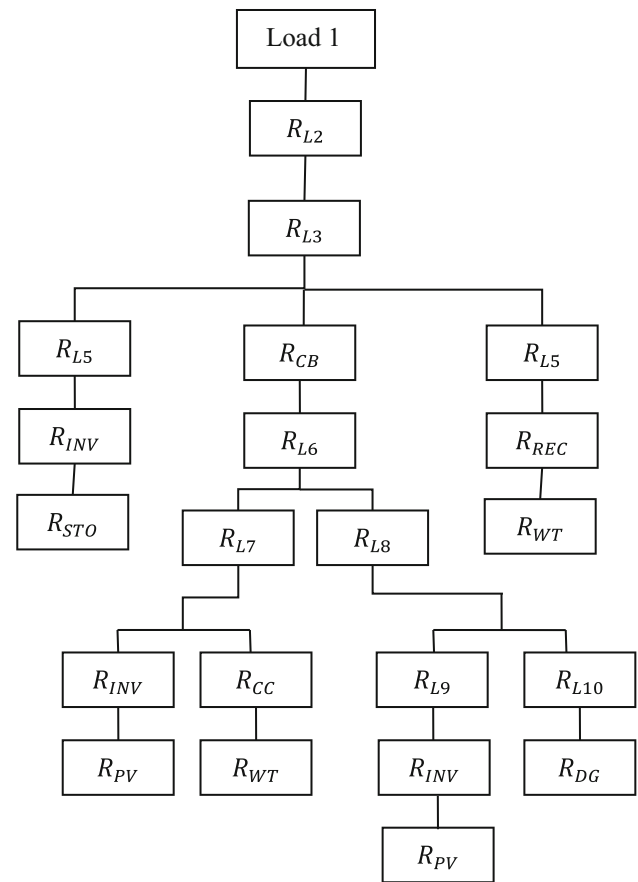


Fig. 9 Reliability block diagram of load point 1

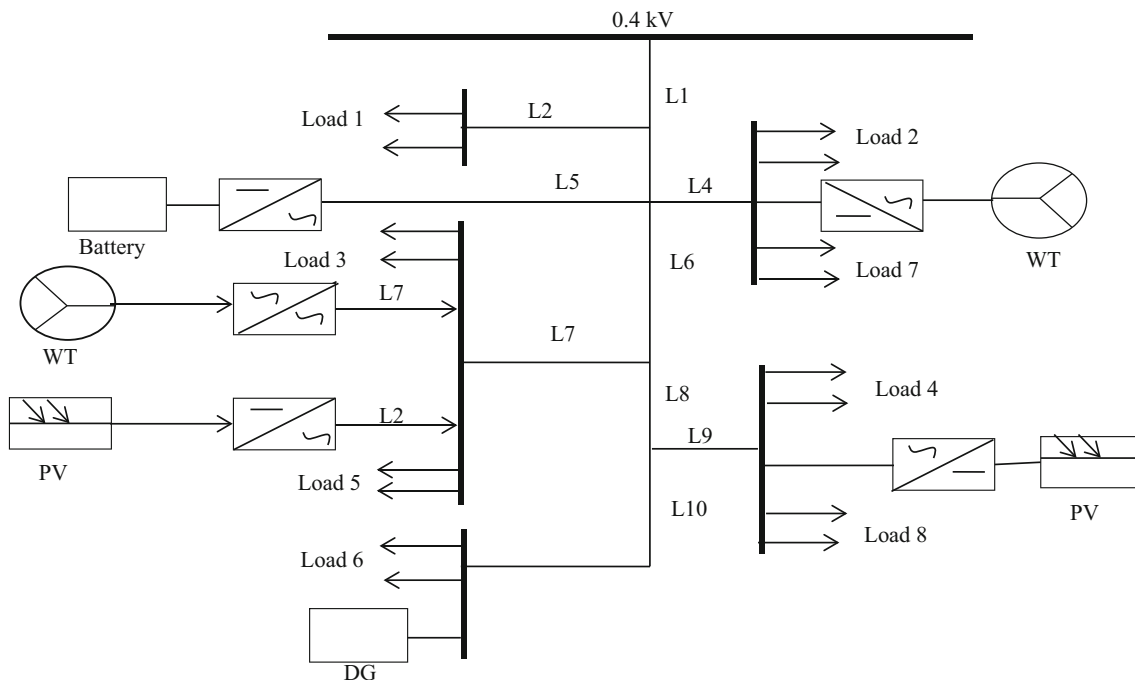


Fig. 8 0.5 kV Benchmark microgrid network

$$R_8 = R_7 x e^{-\lambda_{L9} t} \quad (29)$$

$$R_9 = 1 - (1 - R_8)(1 - R_5) \quad (30)$$

$$R_{10} = R_9 x e^{-(\lambda_{L6} + \lambda_{CB})t} \quad (31)$$

$$R_{11} = e^{-(\lambda_{STO} + \lambda_{INV} + \lambda_{L5})t} \quad (32)$$

$$R_{12} = e^{-(\lambda_{WT} + \lambda_{REC} + \lambda_{L5})t} \quad (33)$$

$$R_{13} = 1 - (1 - R_{10})(1 - R_{11})(1 - R_{12}) \quad (34)$$

$$R_{15} = R_{13} x e^{-(\lambda_{L2} + \lambda_{L3})t} \quad (35)$$

The methodology presented in Eqs. (22)–(35) shows the procedure for the derivations of the reliability model of load point 1. In order to determine the effect of components on the reliability of the microgrid, the models of the component measures and the reliability models of each load are utilized. The standard failure rates in the standard Military Handbook were used in simulating the reliability model of load 1 (Bergmann 1995). The simulation was run for a period of one year, and the results are shown in Table 9.

Components importance analyses process of load 2–8 is the same as load 1. Similarly, the component rank remains the same as load 1. Therefore, the result of the analysis is also the same as shown in Table 9. As indicated by the result, the most important component is the inverter. The components ranked second and third are diesel generator and the storage unit. The least important components are wind turbine and rectifier units. It should be noted that this trend is uniform throughout the analysis. The results obtained from the analysis have indicated that the location of the load on isolated microgrid does not affect the rank contribution of the component to the system reliability. It can be seen that the components that make up microgrid have different levels of importance with respect to the system reliability.

Table 8 shows a representative sample of the result, and it has been observed that the inverter unit has the highest BI measure and CI confirmed the same. The same is true for all cases throughout the analysis; this means the contribution of components to the reliability is the same irrespective of the location of the load.

Table 8 Components importance for load points 1

Components	BI	CI
Rectifier	7	7
Inverter	1	1
Wind turbine	8	8
Converter	6	6
Line	5	5
PV	5	5
Diesel generator	2	2
Storage	3	3

7.5.1 DC-coupled Microgrid

In DC-coupled microgrid configurations, the network that uses only one DC bus such that all the generating units are connected to the DC bus (Saeed et al. 2013). Therefore, it can be observed that all the DC generating sources are connected directly to the DC through the charge controllers for control purpose. The corresponding AC components are connected to the DC bus through rectifier units. One of the concerns with this configuration is that the power generated by the diesel generator is first rectified and then converted back to AC. This process actually reduces the efficiency of the system due to the conversion process. The reliability block diagram of this configuration is presented in Fig. 10 (Zhang et al. 2012). Reliability model of the configuration is obtained as in Eq. (36). Similarly, the rank of each component for this configuration is presented in Tables 9 and 10.

$$R_{DC} = [1 - (1 - R_a)(1 - R_b)(1 - R_c * R_d)(1 - R_e)] \cdot R_{I5} \cdot R_d \quad (36)$$

where R_a, R_b, R_c, R_d, R_e represent the reliability models of wind turbine generator, PV system, diesel generator, bidirectional inverter, storage, respectively. All the models represent the generator and its connecting components.

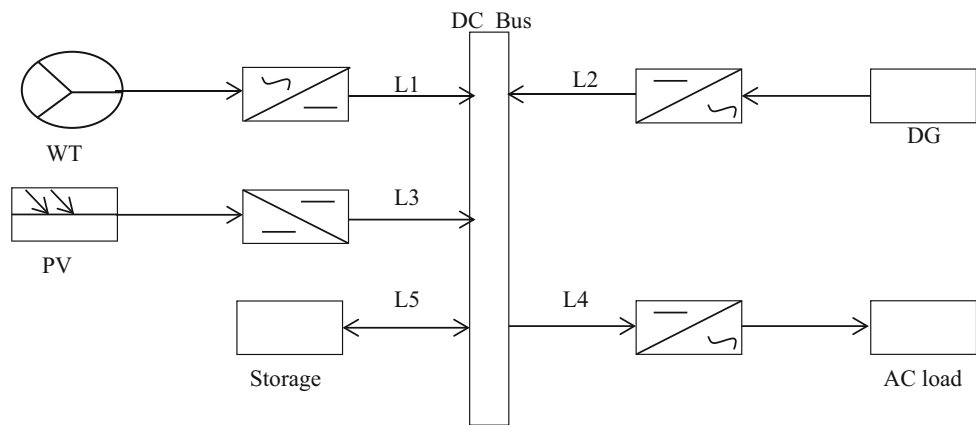
7.5.2 AC-coupled Microgrid

AC-coupled microgrids are based on the fact that all the generating units are connected to the AC bus (Sayeef 2009). It can be observed that all the DC generating sources are connected to the AC bus via inverter units, while the AC counterparts are connected directly to the AC bus. The energy supplied by the storage system is controlled by the bidirectional inverter unit. Some of the benefits of this configuration include easy expansion. The configuration of the network is as shown in Fig. 11 (Sayeef 2009). Similarly, the reliability expression of the load point is obtained using reliability reduction algebra in Eq. (37). In the same way, the corresponding ranking is presented in Tables 9 and 10.

$$R_{AC} = [1 - (1 - R_a)(1 - R_b)(1 - R_c)(1 - R_d \cdot R_e)] \cdot R_{I5} \quad (37)$$

7.5.3 AC–DC-coupled Microgrid

The circuit is configured such that the electricity-generating components are connected to either AC or DC buses depending on the type of generating units (Fateme and Gholam 2011). The link between AC and DC buses is easily established through the bidirectional inverter. The

Fig. 10 DC-coupled hybrid system**Table 9** Components importance analyses of different network structures

Type of coupling	DC coupling		AC coupling		AC–DC coupling	
	BI (pu)	CI (pu)	BI (pu)	CI (pu)	BI (pu)	CI (pu)
Rectifier	2	2	2	2	2	2
Inverter	1	1	1	1	1	1
Wind turbine	8	8	8	8	8	8
Converter	7	7	7	7	7	7
Line	6	6	6	6	6	6
PV	5	5	5	5	5	5
Diesel generator	3	3	3	3	3	3
Storage	5	5	5	5	5	5

Table 10 Components importance analyses of different network structures

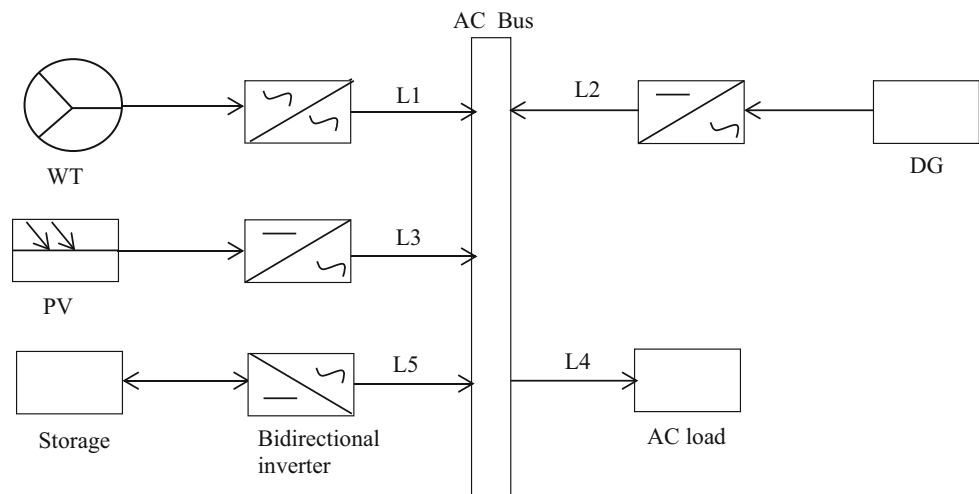
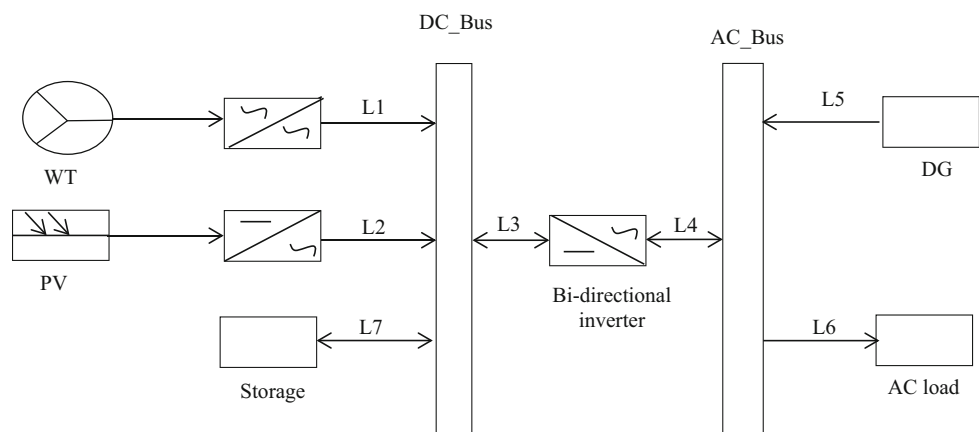
Coupling	DC		AC		AC–DC	
	NRAW	NRRW	NRAW	NRRW	NRAW	NRRW
Inverter	2	1	2	3	2	3
Storage	3	5	5	6	5	5
Wind turbine	7	5	7	2	6	5
Converter	6	2	5	2	5	3
Line	1	1	1	1	3	1
PV	5	6	6	5	6	3
Diesel generator	5	3	3	5	1	2

inverter can operate in parallel with diesel generator; hence, the need to size the inverter equal to at least peak load is eliminated and flexibility is increased thereby maximizing the efficiency of the diesel generator. The network reliability model is obtained as in Eq. (38), and the component ranking is presented in Tables 9 and 10 (Fig. 12).

$$R_{AC-DC} = [1 - (1 - R_x)(1 - R_c)(1 - R_e)] \cdot R_{l6} \quad (38)$$

It can be observed from Table 10 that the components that make up microgrid have different contributions to the system reliability. The rank according to the BI and CI measures of different network structures shows that rectifier > inverter > diesel generator > storage > line >

PV > wind turbine. Among the generating sources, the diesel generator being on standby mode has the highest rank followed by the storage, while the renewable energy sources have the least rank. Therefore, depending on the system requirements, if the objective is to decide on the improvement on the system reliability as a result of each component, BI measure is suitable. On the other hand, if the objective is to prioritize maintenance or improve on the reliability of component with lower reliability, then CI is an appropriate measure. Also, components ranking according to the type of coupling for NRAW and NRRW measures is shown in Table 10. NRAW could be used to identify which component should be maintained well in order that the system reliability not be reduced; on the

Fig. 11 AC-coupled hybrid system**Fig. 12** AC–DC-coupled hybrid system

other hand, the NRRW indicates candidates for redundancy. It is important to note that all of them are candidates in identifying the weakest point that can affect the reliability of the system. In the case of DC microgrid, NRAW shows that line and rectifier–inverter unit have the highest rank, followed by storage, PV, DG, converter, and wind turbine generator in that order. The rank of components is, however, dependant on the coupling bus type. Also, the results have shown that for all the coupling methods, line and inverter are the most important components of the system analysed. This is because the reliability of these components definitely affects the reliability at load points. In addition, the results have indicated that the rank of the component to the system reliability in microgrid depends on the type of coupling. However, the individual component's contribution depends on the network structure.

8 Conclusion

The paper has proposed a new method for reliability analysis of microgrid consisting of renewable energy resources. The proposed microgrid is developed and analysed in a DIgSILENT. The reliability of the developed microgrid is analysed in three levels that is load, busbar and system levels. Effects of various factors on the reliability of the model have been investigated, and the results have shown that increase in the system demand affects the ENS, AENS, EIC and ACCI by almost the same factor at the system level. At a load point, the indices that are sensitive to system demand are LPIC and LPENS. Diesel generator records the least busbar interruption and therefore has least reliability interruption indices. Also, increase in component failure rates increased the system and busbar indices by a very small percentage level, while load point

indices are not sensitive to the component failure rates. Additionally, the effectiveness of the proposed method is evaluated on different microgrid configurations. In the same way, the contributions of each component to the reliability of the system have been investigated by deriving the component importance models of different microgrid structures. This has been achieved by simulating the reliability model of each model according to the reliability. Critical analyses of the results have shown that the inverter and line are the most critical component and hence determine the weakest part of the microgrid. In the same way, NRRW and NRAW ranking shows that the rank of each component depends on the type of microgrid configurations. It is recommended that further reliability analysis could be on the effects of non-electronics components and failure rates of electronics components connected to microgrids. The use of computational intelligence techniques in the reliability study of grid connected and off-grid renewable energy microgrid is also recommended.

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