Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2017) 25: 4657 – 4672
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doi:10.3906/elk-1609-137

Markovian model for reliability assessment of microgrids considering load transfer restriction

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Received: 16.09.2016 • **Accepted/Published Online:** 13.07.2017 • **Final Version:** 03.12.2017

Abstract: Reliability is an indispensable factor in power system design and operation and has a significant impact on grid safety and economy. Future power distribution systems are expected to be more sophisticated, owing to the increasing penetration of renewable resources and adoption of advanced information and communication technologies. Extant studies in this field tend to focus on the modeling and assessment of the reliability of future microgrid distribution systems, including distributed generation, without considering networked configuration and limited transfer capacity. In the work presented in this paper, a Markov model is implemented to perform a practical and accurate reliability evaluation of networked electric microgrids under load transfer restriction conditions. The Markov model is used to model the microgrid based on the connectivity between the source and the loads and to compute load and system reliability indices. Moreover, the distribution load flow (DLF) method is adopted when reclassifying the Markov model states based on the system's transfer capability during interruptions. The obtained results confirm that the proposed model is efficient and that the DLF provides a more accurate reliability analysis due to the computing of the voltage profile during the system outage restoration process. This model can also be used to optimally integrate distributed generators into the power system at proper locations and with proper capacities to enhance the system's reliability.

Key words: Microgrids, Markov model, load flow, power system reliability, distributed power generation

1. Introduction

As the demand for electrical power is continuously growing, reliable electricity provision has become one of the most important targets for utilities. Due to this increasing demand, power systems must provide satisfactory electrical energy with adequate service reliability and quality. Reliability, in general, is the probability that a system will achieve its objective in a satisfactory manner. In the context of power systems, power reliability can be defined as the absence of equipment outages and customer supply interruptions.

Several methods can be adopted for computing reliability indices, which are typically classified into analytical or simulation-based approaches [1]. Some of the analytical techniques are based on reducing system topology by transforming the complex structure into a simpler topology [2–4], while others rely on enumerating the connection sets such as minimal paths and cut sets [5,6]. While these approaches are useful in the cases of simple and small systems, they can be difficult to apply to complex and dense networks. Some algorithms require advanced and complex programing, and some can only be used for specific graph types. Markov modeling is one of the most popular analytical approaches for evaluating power system reliability [7]. When using a Markov model (MM) for evaluating the reliability of complex and large networks, difficulties arise in determining the

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status of each state in the system, as well as in communicating between the states and managing the large size of the state space.

Because the distribution system is the final component in the power system chain and because it is connected directly to the customers, its reliability must be investigated and evaluated. The aim is to ensure electricity delivery to customers at an acceptable level of reliability and identify any required improvements. In response to this need, an ample body of research has been conducted on the reliability of distribution systems and on the most suitable assessment methods. In 1975, Billinton and Grover proposed a direct reliability evaluation method for transmission and distribution systems [8]. Since then, three indices have been widely used in academic research to assess power system reliability, namely frequency of failure, average outage duration, and average total hours of outage in a year.

In 1996, Billinton and Jonnavithula developed an educational test system (RBTS) that incorporated an overall power system reliability assessment [9]. The RBTS system is now widely used in reliability studies. More recently, Liu and colleagues developed a technique for evaluating a distribution system based on a simplified network model and a network equivalent [2]. A method for analyzing and assessing the current reliability of an operational power system with an equivalent model based on a Markov chain was proposed by Wang and colleagues [7]. In most extant studies in this field, a Markov chain is used to evaluate reliability based on the probabilities of system states. The calculations and results reported by these authors indicate that the proposed algorithm is both efficient and practical.

However, large systems are characterized by an extensive number of Markov states, necessitating that analytical methods be replaced by simulation programs. In 2013, reduction and truncation techniques were proposed by Al-Muhaini and Heydt [10] to overcome problems associated with the use of a large number of components and states in Markov matrices. Al-Muhaini and Heydt subsequently expounded on their work by proposing a new approach for evaluating the reliability of a networked distribution system [11]. The evaluation performed as part of this study was based on the connection between source and system loads by determining minimal tie sets. The authors utilized the Markov model, along with reduction techniques, to compute the system's reliability indices.

Reliability improvement and management is one of the key smart grid functions. Extensive review of the pertinent literature, however, has revealed an absence of an automated generalized algorithm that can be applied to evaluate the reliability of a networked power distribution system comprising both conventional and renewable distributed generators (DGs). The impact of the DG on reliability indices has been studied extensively, as evident by the ample body of literature on this topic [12–20]. Most of the DG reliability studies that have been conducted to date were, however, specifically formulated and applied to specific study systems or to radial networks. In 2009, Kennedy [12] presented a method for evaluating local generation adequacy for an islanded microgrid with limited stochastic resources, which was based on a combined generation to load ratio (GLR) model. In [14], an analytical technique based on the Markov process, combined with a frequency and duration technique, was proposed for distribution system analysis that included the incorporated DG. In 2015, Wang and Wang proposed a comprehensive operation and self-healing strategy for a distribution system with both dispatchable and nondispatchable DGs. Adoption of the proposed approach minimizes operation costs in normal operation mode and guarantees reliable power supply to consumers in the event of faults.

The reliability of future networked distribution systems incorporating DGs and load transfer capability has been the topic of a limited amount of research. The work of da Silva et al. [21] is the most notable among studies in which this issue was explored. These authors conducted an impact analysis of distributed energy resource integration on distribution systems with an emphasis on determining the capacity that may be transferred to other feeders. The proposed method was based on the minimal cut-sets and chronological Monte Carlo simulation (MCS). In 2008, Collum et al. [22] examined different load transfer schemes used at utility sites and their operations during system interruptions. They also discussed how the settings could be manipulated to maximize the advantages and minimize the drawbacks of different schemes.

The reliability model presented in this paper is based on Markov chains and is intended for use in microgrid reliability evaluation. The model can be applied in microgrid reliability assessment when the aim is to evaluate transfer capability, networked connection, and the distributed generation of the microgrid. Due to consideration of the complexity of the future power distribution systems, this approach improves the reliability calculation accuracy. The MM states are classified either as up states or down states, based on the connectivity among the source and the loads. In the next section, a distribution load flow analysis is performed to reclassify the states based on the voltage transfer capability from the source to the load. The effect of the voltage profile on the reliability analysis is also investigated. The model developed as a part of the present study is applied to a RBTS Bus 2, which includes mesh connections and distributed generators installed at main feeders.

The main contributions of the proposed model can be summarized as follows:

- Large and complex systems are characterized by an extensive number of Markov states. Hence, difficulties arise in determining the status of each state in the system, as well as in communicating between the states and managing the large size of the state space. The proposed model overcomes the abovementioned limitations and provides an automated generalized algorithm for evaluating the reliability of a networked power distribution system incorporating both conventional and renewable DGs with consideration of load transfer restrictions. Moreover, the proposed model can be utilized to optimally locate and size DGs incorporated into the power system to enhance system reliability and facilitate service restoration.

- The DLF method is integrated in the reliability model to account for the practical consideration of the DG integration and load transfer restrictions. The DLF provides a more accurate reliability analysis by computing the voltage profile of the system. In the MM, voltage violations were considered as failures or down states and were found to negatively affect power system reliability.

2. Reliability evaluation of electric microgrids

The reliability of power systems can be evaluated by computing reliability indices. Two types of indices, load point indices and system indices, are typically utilized for this purpose [23]. Load point indices, including annual availability (A), unavailability (U), average interruption duration (AID), and average interruption frequency (AIF) are calculated for each load point in the system. System indices are computed for the entire system and provide an overall indication of system reliability. The system indices include the system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), and average service availability index (ASAI).

The failure of distribution components causes a disconnection between the load points and the utility source, which results in service interruptions, thereby decreasing system reliability. Transfer capability can also affect the reliability of large-scale distribution systems and microgrids, as these include a large number of nodes and load points, which may introduce high power losses and drop voltages throughout the system. Therefore, delivering an acceptable level of voltage and power to each load point during interruptions is a challenge that must be overcome to ensure adequate system reliability. To mitigate the influence of these two problems, tie switches can be connected between the lines comprising the distribution system as a means of improving connectivity between the source and the loads. The voltage profile and reliability can also be improved by integrating the distribution system with DGs and advanced control systems, thereby creating a microgrid system. A microgrid is an active distribution network, composed of DGs, power electronic interfaces, and a control system, which provides electricity to local areas or customers [24]. The control system ensures compatibility between the microgrids and the main grid, while meeting the requirements and regulations for power safety and reliability. For this reason, a microgrid is considered a single controlled unit by the main power utility.

In this paper, the reliability of a microgrid system is evaluated based on connectivity and transfer capabilities, as these aspects exert a significant influence on reliability. Service is restored by isolating the failed section and closing tie switches between the main feeders, as well as through the contribution of DGs in supplying electrical power.

3. Proposed algorithm for the microgrid reliability evaluation

In this study, the reliability of microgrids is evaluated using MM and DLF analysis. Power system reliability can be assessed by investigating service availability at each load point of the system. To assess system availability, two principles are applied. First, the connections between the source and the loads are examined through all failure scenarios in MM states. In the next step, the DLF method is employed to study transfer capability and to verify the quality of the voltage at each interrupted load point during service restoration. To meet these objectives, system reduction must be performed first. The number of possible states for a binary system is 2^n, where n denotes the number of components. Therefore, in large systems, the number of states can be prohibitively large, necessitating reduction.

In the present work, the reduction techniques proposed by Al-Muhaini and Heydt [10] are applied. The MM states are determined as either up or down based on connectivity by identifying tie and cut sets [11]. More specifically, tie sets represent the up states, whereas cut sets represent the down states. Once the states have been established, the DLF methods proposed by Alsaadi and Gholami [25] are adopted to investigate the voltage profile of the system. For the up states, if the system voltage is within the 1.05–0.95 pu limit, the states remain up and will otherwise change to down state. Once all system states have been ascertained based on connectivity and transfer capabilities, the MM is used to calculate the reliability indices. The flowchart of the proposed method is depicted in Figure 1.

3.1. Reduction process

In power systems, most components can be either be in an up or down state. In large systems, however, the number of states can be extremely large. To overcome this issue, four levels of reduction can be applied to the system, as proposed by Al-Muhaini and Heydt [10]:

1. Removing the irrelevant load points.
2. Removing all lines that are connected to the irrelevant load points, retaining only the main line connected directly to the source.
3. Removing the irrelevant main feeders or irrelevant sections.
4. Considering only states of two simultaneous failures at the maximum because more than two simultaneous failures are highly unlikely in power systems.

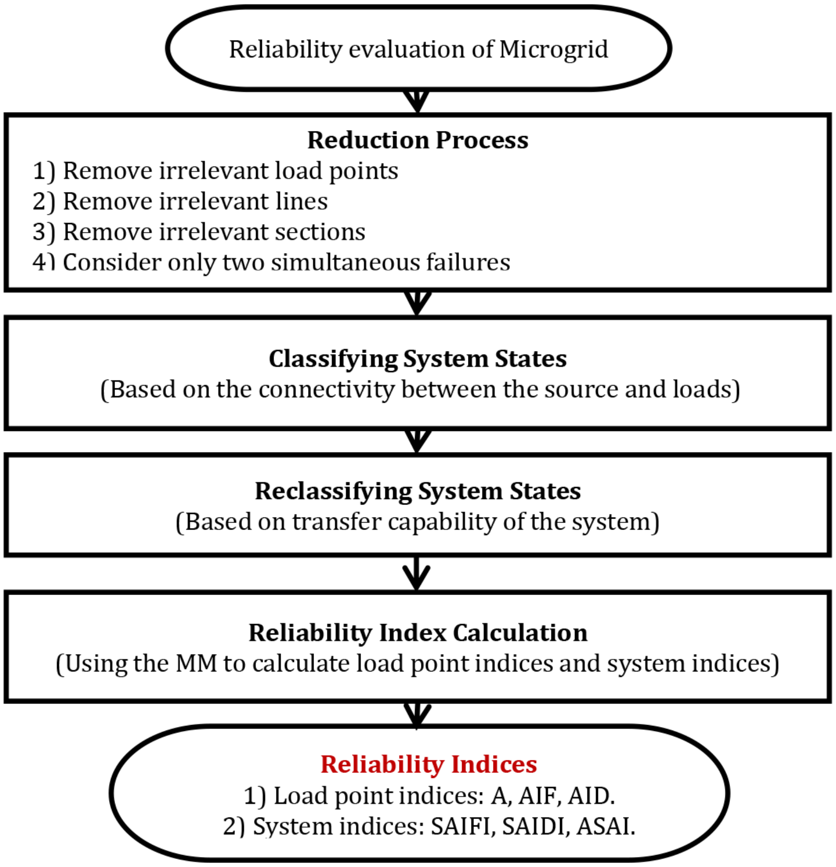

Figure 1. Reliability evaluation flow chart.

3.2. Classifying the states based on connectivity

As previously noted, system states are classified as up or down states, according to the connectivity between the source and the loads. If there is a valid connection between the source and the load, the load is considered to be in an up state and is in down state otherwise. One of the techniques that can be used to analyze the reliability of complex power networks based on their connectivity is the cut and tie set method. When applying this technique, the network is decomposed into a group of subsystems or into a set of components (line sets), allowing system reliability to be determined [1]. These component sets are the tie set (TS), minimal tie set (MTS), cut set (CS), and minimal cut set (MCS). They are defined as follows:

1. TS represents any set of components that creates a path between the source and the load.
2. MTS is a set of minimum components that creates a path between the source and the load. If one of these components fails, there is no connection between the source and the load.
3. CS is a set of components that has to fail to cut the path between the source and the load.
4. MCS is a set of minimum components that has to fail to cut the path between the source and the load. If at least one of these components does not fail, a connection from the source to the load is maintained.

In line with their definitions, TSs and MTSs represent the up states, whereas CSs and MCSs represent the down states. In small systems, these sets of components can be determined by inspection. However, in large systems, the process is more complex. More specifically, to determine the TSs and CSs for large systems, Petri net and prime encoding methods are typically used [11].

3.3. Reclassifying the states based on the transfer capability

In addition to system connectivity, when identifying system states, the voltage profile of the system during the restoration process is also considered in this work. This approach facilitates accurate and practical analysis of power reliability. The DLF method can be utilized to investigate the voltage profile for the states when the system is up (as established by examining the load point due to the restoration of service to that load during the fault). The DLF method is also used to determine whether the system voltage in those states is within the prescribed limits. If the voltage level is breached, the system state will change from up to down. All the system state classifications will be updated based on this assessment.

The DLF method can be applied to directly solve distribution power flow using two matrices: a bus-injection to branch-current (BIBC) matrix and a branch-current to bus-voltage (BCBV) matrix [25]. The BIBC and BCBV matrices are formed according to the system configuration and are utilized for branch current and drop voltage calculations, respectively. Multiplying these two matrices results in the DLF matrix, which is used to compute bus voltages.

Initially, all bus or node voltages are assumed to be equal to the source node. The specified data in the distribution system are the load active power (P) and the reactive power (Q) for each bus. Node currents can be computed in terms of the specified P and Q as follows [25]:

$$I_{node} = \frac{(P + jQ)*}{V*} \frac{(P + Q)^*}{V^*} \tag{1}$$

By applying Kirchhoff's current law to the distribution system, branch currents can then be obtained in terms of node currents. The relationship between branch currents and node currents is given by the following expression [25]:

$$I_{branch} = [BIBC] * I_{node} \tag{2}$$

The relationship between the branch currents and bus voltages can be expressed as [25]

$$V_D = [BCBV] * I_{branch} \tag{3}$$

By substituting Eq. (2) with Eq. (3), we obtain

$$V_D = [BCBV] * [BIBC] * I_{node}$$

$$V_D = [DLF] * I_{node}, \tag{4}$$

where DLF is the DLF matrix. Finally, the bus voltages are computed by

$$V_{Bus} = V_{source} - V_D \tag{5}$$

After solving the voltages for all buses by applying Eq. (5), a convergence check must be performed. If the solution converges, the procedure is terminated; otherwise, the algorithm is executed iteratively until the convergence criteria are met. Figure 2 shows the DLF method algorithm used for ascertaining the voltage at the

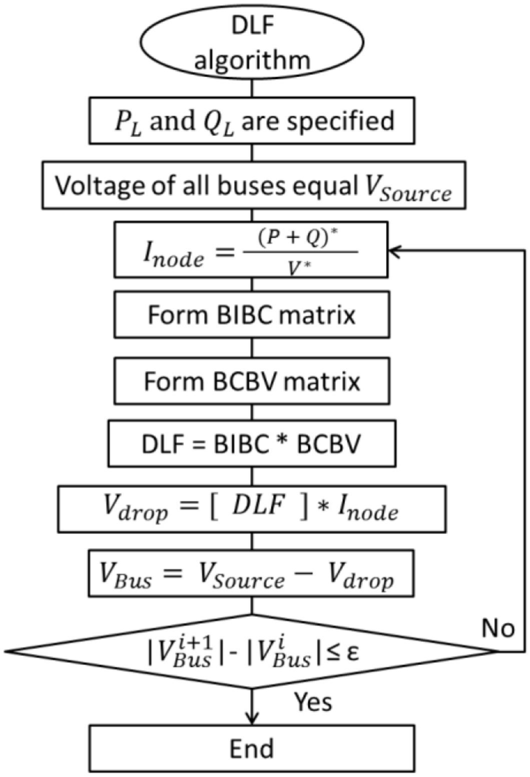

Figure 2. DLF method algorithm.

distributed buses. However, to obtain the voltage at the load point ends, additional calculations are necessary. The current divider rule can be adopted for determining the voltage at each load point.

Distribution generation is a generation system that spreads throughout the distribution system in order to improve service and reliability. DGs could be photovoltaic systems, wind turbines, fuel cells, or microturbines. DG units have different operational modes. For example, they could supply power with a predetermined amount of reactive power (fixed power factor). In this case, DG units do not control the voltage at the connection point. On the other hand, DG units could supply power by controlling and regulating the voltage at the connection points. If a DG unit generates a predetermined amount of power, it is modeled as a PQ bus and is treated as a load bus with negative P and Q values. However, when a DG unit regulates and controls the voltage at the connection point, it is modeled as a PV bus.

In the case of PV, the active DG power P_{DG} is specified. The reactive DG power Q_{DG} is initially set to zero, and the voltage at the P-V node is set to the desired value. The DLF method can be utilized in this case with some adjustments. Branch currents can be calculated by applying the following equation [25]:

$$I_{branch} = [BIBC] * (I_{node} + I_{DG}) \tag{6}$$

After computing the bus voltages, if $|V_i - V_{i-set}| \leq$ error tolerance, the solution has converged. Otherwise, Q_{DG} will be generated by the P-V node to maintain voltage at the specified value. Q_{DG} can be computed as follows [25]:

$$Q_{DG-new} = Q_{DG-old} + Im(V_i \frac{V_i^*}{z}), \tag{7}$$

where i is the number of the DG bus, V_{i-set} is the set voltage at the DG bus, and V_i is the calculated voltage at the DG bus.

3.4. Markov model in reliability evaluation

Markov chains are used to model a sequence of discrete or continuous random variables that correspond to a set of system states. A state transition matrix can mathematically represent the states and transition probabilities. For a system with n discrete states, $\mathrm{S}_1, \mathrm{S}_2, \ldots, \mathrm{S}_n$ and ρ_{ij} determines the transition from one state to another (thus corresponding to the rate of departure).

In a power system, most components have only two possible states: up or down. Here, it is assumed that state i is an up state and state j is a down state. Consequently, the transition ρ_{ij} from the up state (i) to the down state (j) corresponds to the failure rate (λ_{ij}), whereas the transition (ρ_{ji}) from the down state (j) to the up state (i) is equivalent to the repair rate (μ_{ii}). System states are classified as either an up or down state based on connectivity and transfer capabilities. To obtain time-dependent system state probabilities, the Markov differential equation must be solved [11]. This general equation can be written in the matrix form, where $i = 1, 2, \ldots, n$, as follows:

$$\begin{bmatrix} p_1'(t) \\ p_2'(t) \\ \vdots \\ p_n'(t) \end{bmatrix} = \begin{bmatrix} -\sum\limits_{j=2}^{n} \rho_{1j} & \rho_{21} & \cdots & \rho_{n1} \\ \rho_{12} & -\sum\limits_{\substack{j=1 \\ j\neq 2}}^{n} \rho_{2j} & \cdots & \rho_{n2} \\ \vdots & \vdots & \cdots & \vdots \\ \rho_{1n} & \rho_{2n} & \cdots & -\sum\limits_{j=1}^{n-1} \rho_{nj} \end{bmatrix} \begin{bmatrix} p_1(t) \\ p_2(t) \\ \vdots \\ p_n(t) \end{bmatrix} \tag{8}$$

These differential equations can be solved under the steady-state condition ${p_i}'(t) = 0$ for $i = 1, 2, \ldots, n$, and the summation of each row is equal to one. The steady-state probabilities P_i can then be computed. Finally, the load point reliability indices and system reliability indices can be calculated [11].

4. Integrated test bed application for the proposed algorithm

The model developed as a part of the present study was implemented in the RBTS-Bus 2 system, as shown in Figure 3 [11]. The base voltage of this distribution system is 11 kV, and it has 22 load points and 36 feeders. The component, customer, and reliability data for the RBTS-Bus 2 are presented in Tables 1, 2, and 3 [23]. In the power flow analysis, a peak load with a power factor of 0.9 is considered, and the system lines or components are treated as overhead lines.

Five case studies were conducted in order to test the model, including DGs with different capacities and locations to investigate the impact of the DGs on system transfer capability and reliability. The specifications of these case studies are given below:

1. Weakly meshed RBTS-Bus 2 without DGs, as shown in Figure 3.
2. Two DGs modeled as a PQ bus are installed at Bus 3 and Bus 9. The DGs generate 200 kW with 0.8 PF.
3. The 2 PQ-DGs are installed at Bus 5 and Bus 15.

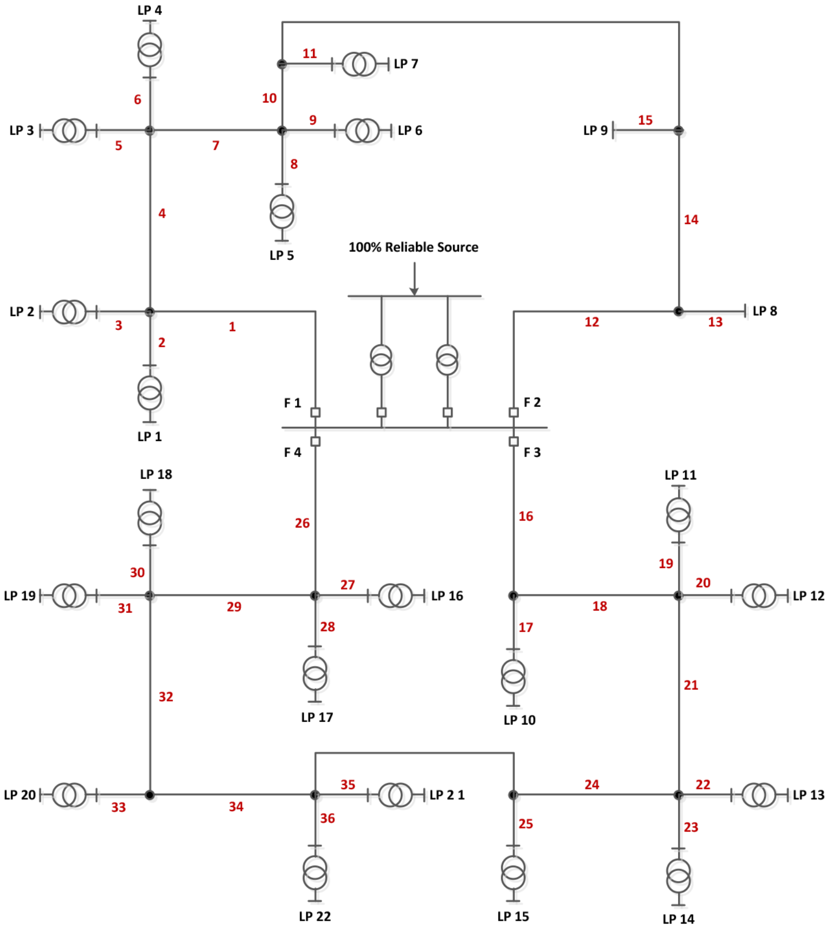

Figure 3. Single line diagram of RBTS-Bus 2 [11].

Table 1. Lines reliability data: RBTS Bus 2.

Section number	Length (km)	Overhead lines			Underground cables		
		Failure rate (f/y)	Repair rate (r/y)	Repair time (h)	Failure rate (f/y)	Repair rate (r/y)	Repair time (h)
2, 6, 10, 14, 17, 21, 25, 28, 30, 34	0.60	0.03900	1752	5	0.024	292	30
1, 4, 7, 9, 12, 16, 19, 22, 24, 27, 29, 32, 35	0.75	0.04875	1752	5	0.030	292	30
3, 5, 8, 11, 13, 15, 18, 20, 23, 26, 31, 33, 36	0.80	0.05200	1752	5	0.032	292	30

Table 2. Transformers reliability data: RBTS Bus 2.

Component	Type	Failure rate (f/y)	Repair rate (r/y)	Repair time (h)	Replacing rate (r/y)	Replacing
37–56	11/0.415	0.015	43.8	200	876	10

Table 3. Load data: RBTS Bus 2.

Loads	Feeder	Type	Average load (MW)	Peak load (MW)	Number of customers
1	F1	Residential	0.535	0.8668	210
2	F1	Residential	0.535	0.8668	210
3	F1	Residential	0.535	0.8668	210
4	F1	Gov/Inst	0.566	0.9167	1
5	F1	Gov/Inst	0.566	0.9167	1
6	F1	Commercial	0.454	0.75	10
7	F1	Commercial	0.454	0.75	10
8	F2	Small user	1	1.6279	1
9	F2	Small user	1.15	1.8721	1
10	F3	Residential	0.535	0.8668	210
11	F3	Residential	0.535	0.8668	210
12	F3	Residential	0.45	0.7291	200
13	F3	Gov/Inst	0.566	0.9167	1
14	F3	Gov/Inst	0.566	0.9167	1
15	F3	Commercial	0.454	0.75	10
16	F4	Commercial	0.454	0.75	10
17	F4	Residential	0.45	0.7291	200
18	F4	Residential	0.45	0.7291	200
19	F4	Residential	0.45	0.7291	200
20	F4	Gov/Inst	0.566	0.9167	1
21	F4	Gov/Inst	0.566	0.9167	1
22	F4	Commercial	0.454	0.75	10

4. Two DGs modeled as a PV bus are installed at Bus 3 and Bus 9. The DGs generate 800 kW with a maintained voltage of 1 pu at the DG buses.

5. The 2 PV-DGs are installed at Bus 5 and Bus 15.

The system under consideration has 56 components, including lines and transformers. Thus, the number of states before reduction is $2^{56} = 7.2058 \times 10^{16}$, which is extremely large and impractical for computation. After applying the four levels of reduction, the final number of components in Section 1 and Section 4 are, respectively, 7 components with 29 states and 9 components with 46 states for each load point.

The system states at each load point are initially classified as either up or down, based on connectivity, before being reclassified according to transfer capacity. Table 4 shows the classification of the states for LP1 in Case Study 1. At each state, components with the value of 1 are denoted as up, while those with the value 0 are down.

All up states presented in Table 4, with the exception of State 7, have a voltage within the prescribed limits at the connection point of LP1. As the voltage in State 7 is below the required range, its state changes from up to down. Moreover, at this state, Component 1 fails and becomes isolated from the system. As a result, only one main feeder (Feeder 2) feeds the system, leading to weak voltage at the end of the line. Consequently, State 7 represents the restoration state for LP1 when there is a failure in Component 1. After identifying all the states of all load points in the system, the probabilities of these states, along with the load point indices and system indices, can be computed.

Table 4. State classifications of LP1: Case Study 1.

State	Component number							Classification		
	1	2	3	4	5	6	7	Connectivity	(V) pu	T.C.
1	0	0	1	1	1	1	1	D	0	D
2	0	1	0	1	1	1	1	D	0	D
3	0	1	1	0	1	1	1	D	0	D
4	0	1	1	1	0	1	1	D	0	D
5	0	1	1	1	1	0	1	D	0	D
6	0	1	1	1	1	1	0	D	0	D
7	0	1	1	1	1	1	1	U	0.930	D
8	1	0	0	1	1	1	1	D	0	D
9	1	0	1	0	1	1	1	D	0	D
10	1	0	1	1	0	1	1	D	0	D
11	1	0	1	1	1	0	1	D	0	D
12	1	0	1	1	1	1	0	D	0	D
13	1	0	1	1	1	1	1	D	0	D
14	1	1	0	0	1	1	1	U	0.995	U
15	1	1	0	1	0	1	1	U	0.995	U
16	1	1	0	1	1	0	1	U	0.995	U
17	1	1	0	1	1	1	0	U	0.995	U
18	1	1	0	1	1	1	1	U	0.995	U
19	1	1	1	0	0	1	1	U	0.991	U
20	1	1	1	0	1	0	1	U	0.991	U
21	1	1	1	0	1	1	0	U	0.991	U
22	1	1	1	0	1	1	1	U	0.991	U
23	1	1	1	1	0	0	1	U	0.987	U
24	1	1	1	1	0	1	0	U	0.987	U
25	1	1	1	1	0	1	1	U	0.987	U
26	1	1	1	1	1	0	0	U	0.981	U
27	1	1	1	1	1	0	1	U	0.977	U
28	1	1	1	1	1	1	0	U	0.981	U
29	1	1	1	1	1	1	1	U	0.988	U

In Case Study 2, the reduction and classification are performed based on connectivity, in line with the process adopted in Case Study 1 because there is no change in system topology. However, after including two DGs, the DLF must be conducted again. The two DGs are modeled as P-Q units, characterized by a 200 kW power production capacity and a power factor of 0.8, as shown in Figure 4. The DLF method with the equations for DG is applied to the RBTS-Bus 2 for all load points.

The voltage profile noticeably improves due to the contribution of the DGs. Voltage at LP1 in State 7 increases from 0.9302 pu to 0.9580 pu, its state changing from down to up. States 19–29 are also enhanced, but as they are already up states their status remains unchanged. DLF is applied to all load points in Case Study 2 to obtain the system voltages with the DGs. The voltage profile improvement ranges from 0.67% to 3.25%.

Maximum improvement is obtained at LP3 and LP4 because they are connected to Bus 3, where the

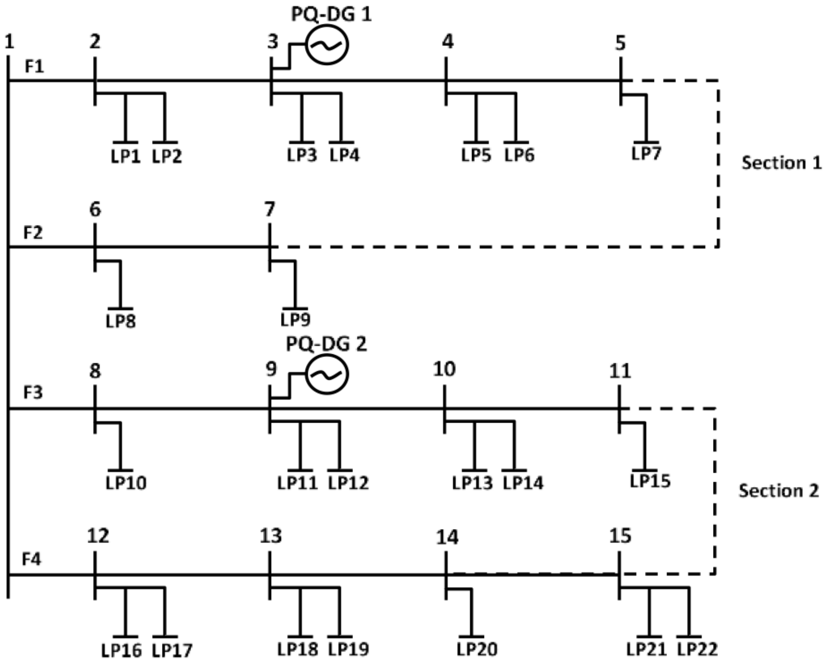

Figure 4. Single line diagram of RBTS-Bus 2 with two PQ-DGs: Case Study 2.

DG is installed at Section 1. Due to voltage enhancement, some states that were previously down as a result of weak voltage have been changed to an up state. On the other hand, all other states that were down based on connectivity remain in this state because no modifications have been made to the network structure. The number of states that change from down to up due to the contribution of the DGs in Case Study 2 are shown in Figure 5.

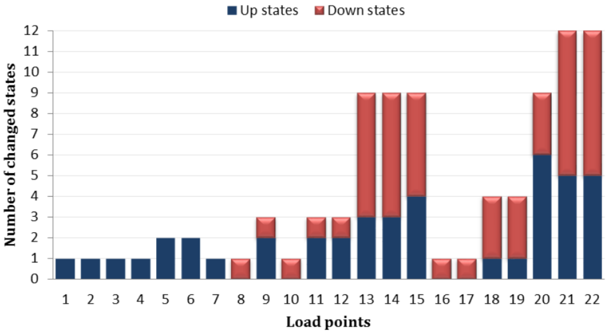

Figure 5. Changed states from down to up after integrating DGs: Case Study 2.

Figure 6 shows the voltage profile of RBTS-Bus 2 Section 1 at State 7 for all cases. In Case Study 1, only the main 11-kV substation feeds the system. This is why many voltage violations occur, especially at the end of the lines, where the voltage is weaker. Installing the 200-kW DGs in Case Studies 2 and 3 improves the voltage profile up to a certain limit and eliminates some of the voltage violations. The voltage enhancement in Case Study 2 is slightly better than that obtained in Case Study 3 in this particular scenario because the latter includes DGs at the ends of Line 1 and Line 3 with insufficient power to affect the entire system. In Case Studies 4 and 5, the capacity of the DGs is increased to 800 kW, which greatly improves the voltage. In Case Study 4, a better voltage is obtained at the beginning of the feeders compared with Case Study 5, whereas the voltage at the ends of the lines is better in the latter case. Overall, the system analyzed in Case Study 5 yields the greatest voltage improvements.

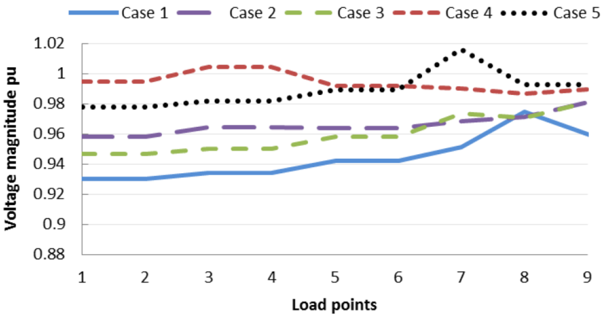

Figure 6. Voltage profiles for all cases at Section 1 of State 7.

Table 5 shows the number of voltage violations identified in each case study. Because RBTS-Bus 2 includes a large number of nodes and load points, the greatest number of under-voltage conditions is obtained in Case Study 1. The inclusion of DGs improves the voltage profile, which in turn reduces the number of voltage violations. Therefore, no voltage violations occur in Case Study 5 due to the appropriate location and capacity of the DGs.

Table 5. DG and voltage violation data.

	Case 1	Case 2	Case 3	Case 4	Case 5
DG Model	-	P-Q	P-Q	P-V	P-V
DG Location	-	3 and 9	5 and 15	3 and 9	5 and 15
DG Capacity	-	200 kW	200 kW	800 kW	800 kW
Voltage Violations	90	45	28	19	0

The AID and AIF for all case studies are shown in Figure 7. The AID measures the duration of time when the system is unavailable. Moreover, as it is directly proportional to unavailability, higher AID values indicate degraded reliability. The highest AID values were obtained in Case Study 1, and they were lowest in Case Study 5. The AIF measures the failure frequency and is related to the number of system down states. Therefore, a higher AIF was obtained in Case Study 1 due to the large number of down states.

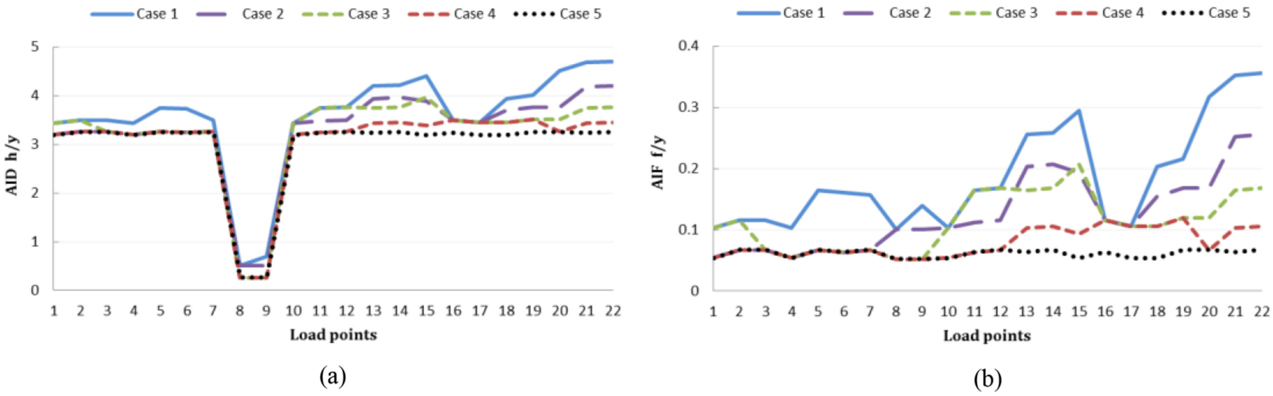

Figure 7. AID and AIF for all case studies: a) AID, b) AIF.

The system indices, i.e. SAIFI, SAIDI, and ASAI, for all case studies are shown in Table 6. As can be seen from the tabulated data, the SAIFI and SAIDI values decrease as the number and duration of interruptions decrease. The best SAIFI and SAIDI values are obtained for Case Study 5, as shown in Table 5. The system in Case Study 3 has a higher SAIFI and SAIDI than those obtained in Case Study 2. This result is attributed to higher AIF and AID values in Case Study 3 between load points 1 and 2 and between 11 and 12 when compared with those in Case Study 2. These load points represent residential areas with a large number of customers.

Table 6. System indices for all case studies.

System indices	Case 1	Case 2	Case 3	Case 4	Case 5
SAIFI (f/c.y)	0.14522	0.10565	0.11677	0.07801	0.06093
Improvement		27%	19%	46%	58%
SAIDI (h/c.y)	3.64704	3.44917	3.50479	3.31094	3.22552
Improvement		5%	4%	9%	11%
ASAI	0.99958	0.99961	0.99960	0.99962	0.99963
Improvement		0.003%	0.002%	0.004%	0.005%

5. Conclusion

In this work, a reliability model based on Markov chains was developed and implemented in order to evaluate the reliability of electric microgrids. The model was utilized when assessing microgrid reliability, while considering transfer capability, networked connections, and the integration of distributed generation. DLF analysis was also performed to provide more practical and accurate reliability indices by validating the system voltage profile in each service restoration state of the system. The states of the Markov chains were initially classified based on the connectivity between the source and the load points, while the DLF was subsequently employed to reclassify the states according to the system's transfer capability. The model was applied to the RBTS-Bus 2 system, and five case studies were performed to test its performance.

In Case Study 1, the voltage gradually weakened towards the feeder ends due to the large number of nodes and load points. Therefore, a significant number of down states occurred, due to the under-voltage conditions, and this resulted in reduced reliability. In the remaining case studies (2–5), DGs were installed in the system, which improved the voltage profile. Integrating DGs into the power system at proper locations and with proper capacities improved the system voltage profile, which in turn reduced the number of under-voltage conditions.

The proposed model provides an automated generalized algorithm that overcomes the limitations and difficulties associated with evaluating the reliability of complex and networked microgrids, including DGs. Load transfer restriction is incorporated in this model to account for the practical limitations of distribution systems during the service restoration phase. The proposed model can also be utilized to optimally locate and size DGs incorporated into the power system to enhance its reliability and facilitate service restoration. Moreover, the DLF provides a more accurate analysis of reliability by computing voltage violations, which were considered failures or down states in the MM and were shown to negatively affect power system reliability.

Abbreviations

MM	Markov Model
DG	Distributed Generators
GLR	Generation to Load Ratio
BIBC	Bus-Injection to Branch-Current
BCBV	Branch-Current to Bus-Voltage
A	Availability

U	Unavailability
AID	Average Interruption Duration
AIF	Average Interruption Frequency
SAIFI	System Average Interruption Frequency Index
SAIDI	System Average Interruption Duration Index
ASAI	Average Service Availability Index
MCS	Monte Carlo Simulation
TS	Tie Set
MTS	Minimal Tie Set
CS	Cut Set
MCS	Minimal Cut Set

Acknowledgment

The authors acknowledge the support of King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, through grants RG1402-1 and RG1402-2.

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