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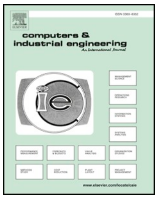

A reliability evaluation method for radial multi-microgrid systems considering distribution network transmission capacity

Yi Ren, Bofeng Cui, Qiang Feng*, Dezhen Yang, Dongming Fan, Bo Sun, Mengmeng Li

School of Reliability and Systems Engineering, Beihang University, Beijing, PR China

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ABSTRACT

The multi-microgrid (MMG) system is studied as a rudiment of the smart grid, and the radial MMG system is regarded as the comprehensive and typical one. The reliability evaluation of MMG systems are widely discussed to ensure its reliable and steady operation. The power balance between supply and demand is the core criterion for the reliability evaluation of MMG systems, which will be broken by unexpected events or inherent limits, such as the failure of equipment and the insufficient transmission capacity of distribution network (DN). In existing research, few have established a reliability model considering partial failure and imperfect repair of the equipment, and the DN transmission capacity usually is ignored. In this study, we abstract the radial MMG system as a performance-sharing system and present a Bayesian-network-based (BN-based) unified modeling method for performance and reliability to solve the deficiencies in existing research. First, the operation of radial MMG systems is analyzed to establish an abstract model to simplify the problem. Afterwards, the executive program of the BN-based reliability evaluation method is given. Further, the system modeling and the BN parameter modeling are introduced. Finally, a radial MMG system including 9 microgrids (MGs) is studied as a case, the variation of the system reliability index in grid-connected and island modes is analyzed. The results show that the method supports the reliability evaluation and analysis of radial MMG systems considering unexpected events and inherent limits.

1. Introduction

The concept of an MMG is developed on the EU's "More Microgrid" program proposed in 2006 (Xu et al., 2018), which forms at the medium-voltage (MV) level, and consists of several low-voltage (LV) MGs and distributed generation (DG) units connected to adjacent MV feeders (Gil & Lopes, 2007). With the popularization of renewable energy power generation, an increasing number of neighboring MGs interconnected to the DN will form a multilevel (and high-voltage) radial MMG system in a wide area (Madureira et al., 2011), which is more typical representative of the future grid. The radial MMG systems are regarded as the rudiment of the smart grid, which have the complex architecture, energy dispatch and failure modes.

Compared to traditional power systems, the reliability evaluation of MMG systems is more difficult due to its more complex structure and operating modes. MG is an independently operating unit in an MMG system, and there are many reliability evaluation methods of MG. The typical characteristics of the MG, such as uncertainties, energy storage, and multiple operating modes, are taken into account in existing methods (Bae & Kim, 2008; Bai, Miao, Zhang, & Bai, 2015; Conti, Nicolosi, & Rizzo, 2012; Conti, Rizzo, El-Saadany, Essam, & Atwa, 2014; Costa & Matos, 2009; Moslehi & Kumar, 2010); which are the foundation of MMG reliability evaluation.

The MMG reliability evaluation method has the following development trend: first, it only focused on the power balance between supply and demand, for example, Nikmehr and Najafi-Ravadanegh (2015, 2016) optimized power dispatch of an MMG system constructed by three interconnected MGs and evaluated the satisfaction of loads demands. However, equipment failure and maintenance will affect system reliability seriously, which is gradually taken into account in the latter methods. In general, the equipment has some intermediate states in addition to the states of "normal" and "failure". For example, in a DG consisting of multiple diesel units, if one unit fails while the others generate power properly, the system is in the state of derating operation, which is an intermediate state. This state, which was ignored completely in the existing reliability model of the MMG, is called partial failure.

In the existing studies, although the reliability evaluation objects

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* Corresponding author.

E-mail addresses: renyi@buaa.edu.cn (Y. Ren), bofeng_cui@buaa.edu.cn (B. Cui), fengqiang@buaa.edu.cn (Q. Feng), dezhenyang@buaa.edu.cn (D. Yang), sunbo@buaa.edu.cn (B. Sun).

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are all called the MMG system, the structures of MMG are totally different. At first, scholars evaluated the reliability of power systems including MG. For instance, Bie et al. (2012) used a non-sequential Monte Carlo simulation (MCS) to evaluate the reliability of an active power distribution system including MGs under single or multiple contingency events. With the maturity of MG technology, MMG systems have two trends in structure. One mode is that multiple MGs interconnected to form an MMG system by dedicated busbars, which is often in remote local areas. The advantage of this mode is the relatively simple architecture, and there are rich researches on system optimization for enhancing reliability: Arefifar, Mohamed, and Elfouly (2013) presented a systematic and optimized strategy for designing MGs. Gazijahani and Salehi (2018) proposed an integrated method relies on cooperation of demand response programs and energy deployment with aim to reliability-oriented planning of MMG. The other mode is that the MGs are connected to the DN directly and operate under the coordination of the DN system operators (DSO). This mode relies on the existing DN technology, which is the future development trend of the MMG. Some scholars have proposed reliability evaluation methods for such systems, for example, Farzin, Fotuhi-Firuzabad, and Moeini-Aghtaie (2017, 2018) developed a general framework based on the MCS method for the reliability evaluation of MMG systems. This model is also the research object of this paper. For this mode, much attention were paid to MGs, however, DN capacity constraints and the reliability of DN equipment were ignored.

There are other academic achievements on the reliability evaluation of MMG systems. In order to improve the efficiency of the MMG reliability evaluation algorithm, Su, Cheng, Zhang, and Wei (2017) proposed a parallel-computing-based reliability evaluation method with consideration of interactions between MGs. In order to describe the operating status of the MMG system comprehensively, Wang, Zhang, Wu, and Sun (2018) presented a set of new metrics for quantitatively evaluating the performance of MMG systems in island mode. These achievements have also promoted the development of MMG reliability evaluation technology greatly. This paper compares various factors considered by existing study when evaluating reliability, as shown in Table 1.

The existing MMG reliability evaluation methods are almost based on MCS. However, the universal performance-sharing system reliability modeling method provides an analytical method for MMG reliability evaluation. The reliability of performance-sharing systems was first studied by Lisnianski and Ding (2009), where a system with two connected multistate units shares the surplus performance from the reserve unit to the main unit. Levitin (2011) extended the study to a multidirectional performance transmission system. Since then, the performance sharing system has become a research hotspot for scholars. Many studies focused on the common bus and units of the system. For common bus, the system with multiple common buses (Peng, Liu, & Xie, 2016), the system considering transmission loss (Qiu & Ming, 2019) and the system with the limited common bus (Peng, Xiao, & Liu, 2017) are studied respectively. For units, the parallel system (Xiao & Peng, 2014); the phased-mission system (Yu, Yang, Lin, & Zhao, 2017; Yu, Yang, & Zhao, 2018); the k-out-of-n system (Zhao, Wu, Wang, & Wang, 2018), systems with common cause failures (Yu et al., 2017) and the warm standby system (Jia, Ding, Peng, & Song, 2017) are concerned. In addition, scholars also analyzed the reliability of the system considering units failures and maintenance (Levitin, Xing, & Huang, 2019; Yu, Yang, & Mo, 2014). These analytical methods provide a modeling scheme for the reliability evaluation of MMG systems.

In order to satisfy the requirements of the radial MMG system reliability evaluation and analysis, a BN-based unified modeling method for performance and reliability is proposed, which considers the partial failure and imperfect repair of equipment and the transmission capacity of the DN. Taking the power balance between supply and demand as a guide, this study simplifies the internal structure of an MG, and abstracts the radial MMG system as a performance-sharing system. Then,

Table 1
Differences between the exiting evaluation methods of the MMG systems.

References	Supply-demand balance	Equipment failure			Transmission capacity	The radial MMG system	Method	Other
		Distribution network	Other equipment	Partial failure				
(Nikmehr & Najafi-Ravadanegh, 2015, 2016)	√	×	×	×	×	×	MCS	Optimal operation
(Bie et al., 2012)	√	×	√	×	×	×	MCS	–
(Arefifar et al., 2013)	√	–	√	×	–	×	–	Optimum design
(Gazijahani & Salehi, 2018)	√	–	√	×	–	×	–	DRP
(Farzin et al., 2017)	√	√	√	×	×	×	Non-sequential MCS	Vehicle-to-grid program
(Farzin et al., 2018)	√	√	√	×	√	×	sequential MCS	Outage management strategy
(Su et al., 2017)	√	×	√	×	×	×	–	Parallel computing algorithm
(Wang et al., 2018)	√	×	√	×	×	×	–	New reliability metrics

the discrete-state continuous-time (DSCT) Markov stochastic process is used to model the failures and maintenance, and Bayesian networks (BN) are used to calculate and analyze power balance. The method proposed will guide the design, operation and maintenance of the system in the future. In addition, this method is also applicable to reliability evaluation of performance-sharing system.

The rest of the paper is organized as follows. A radial MMG system oriented to performance sharing is introduced in Section 2. Then, a BN-based reliability evaluation method for the abovementioned radial MMG system is proposed in the third section, and the system model and BN parameter model are introduced in Section 4. Section 5 presents a case of a radial MMG system with 9 MGs to verify the proposed methods; system reliability is analyzed via fault injection. Finally, we draw conclusions in Section 6.

2. Modeling of a radial MMG system oriented to performance sharing

2.1. Description of the radial MMG system

In the market operation of grids, MGs can be connected to the utility grid and either supply or absorb power from other MGs or from the utility grid (Nikmehr & Najafi-Ravadanegh, 2016). When a greater number of MGs are connected to the utility grid, the radial MMG systems are formed in wide areas.

A typical radial MMG system, as shown in Fig. 1, consists of multiple MGs, a DN, and a control system. The entire system can be divided into two layers: "the MG layer" and "the HV/MV bus bar and substation layer". The MG layer is in the LV layer. Each MG contains DGs, energy storage systems (ESS) and load, and the Point of Common Coupling (PCC) controls the connection and disconnection between the MG and the DN. The microgrid central controller (MGCC) can deal with data of MG, such as power generation, load demand and surplus or shortage of power performance (Hemmati, Amjady, & Ehsan, 2014). The HV/MV bus bar and substation layer are responsible for energy dispatch among MGs. The remote terminal unit (RTU) manages the connection and disconnection between the HV bus bar and the MV bus bar by controlling the substation. To share power among MGs and achieve supply-demand balance, the available data in each MGCC are transmitted to the central autonomous management controller (CAMC) which analyzes the statistics data and dispatches the surplus power.

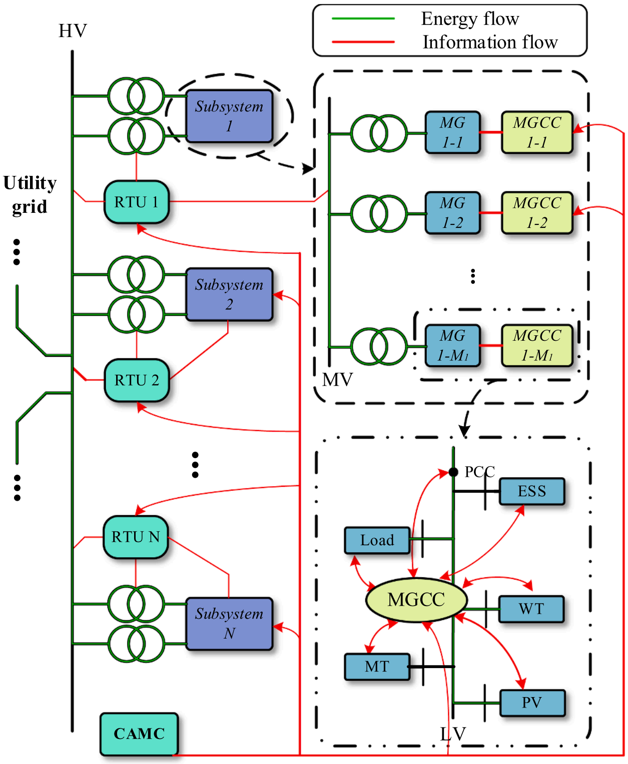

Fig. 1. Architecture and control of a radial MMG system.

The MMG model discussed in this paper is developed on the existing DN architecture, and the DSO supports the MG individual to be connected to the grid, making this MG part of the power system. DSO is the leader in MMG systems and is responsible for the coordinated dispatch of power resources. The cost of the DN and the MG is borne by the individual respectively. DSO is an intermediary of electricity trading and gains profits through electricity trading.

2.2. Basic assumptions

To simplify modeling, the following basic assumptions are proposed.

1) The communication networks for information delivery and the central controller are independent and reliable.
2) The following assumptions are proposed for the discrete state:
a) For discrete generated energy, the generated energy in each MG are a series of continuous values because of renewable energy uncertainty. In this study, it is assumed that the performance output is discrete.
b) For discrete load demand, the intermittent load and adjustable load make the load demand continuous. In this paper, it is assumed that load demand is discrete.
3) The following assumptions are made about parameter independence, which does not isolate the physical structure of the radial MMG system:
a) The generated energy and load demand of the MGs are independent, which means that the generated energy of the generation unit does not affect load demand.
b) Any two MGs in the radial MMG system are independent, which means that the generated energy and load demand of an MG are not affected by other MGs.
c) The transmission capacity of the DN is independent, which means that the transmission capacity of a bus bar does not affect other transmission capacities.

2.3. A formal description of the radial MMG systems oriented to performance sharing

According to research on the architecture, control and management (Madureira et al., 2011), the radial MMG system is abstracted into a model of the performance-sharing system shown in Fig. 2. In the model, MGs can both supply and consume energy and the DN is simplified into bus bar. Multiple MGs connected to the same MV bus bar form a

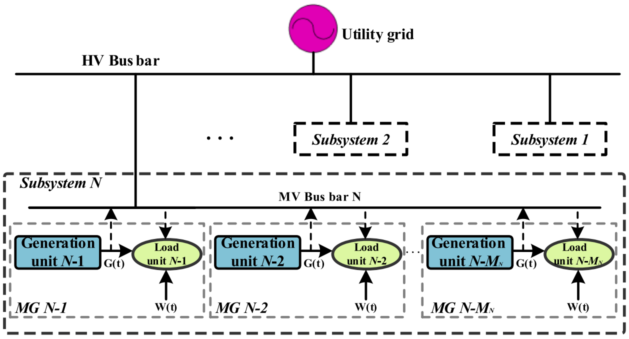

Fig. 2. Abstract model of a radial MMG system that oriented to performance sharing.

subsystem, and the radial MMG system consists of a HV bus bar and N subsystems.

According to the discrete state assumption, the MGs and the bus bar have multiple states. The generated energy of DG is called the performance level. At the same time, the power consumed by loads is called the demand level. The generated energy of an MG is prioritized to satisfy its own load demands. Without considering the performance transmitted among MGs, when the performance level of an MG is greater than its demand level, the MG will have "surplus performance"; in contrast, when the demand level is greater than its performance level, the MG is in a state of "performance deficiency". In addition, the limited transmission capacity of DN is called the transmission level. An MG with surplus performance can deliver performance to an MG that experiences a performance deficiency through DN.

A reasonable energy dispatch strategy can promote performance balance between supply and demand and increase system reliability. As an independent individual, the MG must give priority to satisfying its own load demands. If the power resources of the MG are surplus, the surplus resources are dispatched by the DSO. If the power resources are not enough, the DSO will provide power resources to MG. In order to reduce the loss during power transportation, DSO will dispatch power resources nearby. Therefore, the following strategies are given based on the independence of the MGs and the principle of proximity dispatching:

1) The MG can share surplus power resource with other MGs only when satisfying its own load demand.
2) The exchange power between MG and the DN is limited, and cannot exceed the transmission capacity of DN.
3) Surplus power is prioritized for transferring to the nearest MG. In other words, Surplus power is prioritized for sharing within subsystem (first performance sharing) and then shared among subsystems (second performance sharing).

The ultimate goal of the power system is to satisfy the demands of all loads. In this study, the probability that all MGs satisfy the demands at a certain moment is called "the system instantaneous availability", which is an important indicator of the reliability of the radial MMG system. According to the above definition, the availability of MMG is limited by the power generation capacity of the DG and the transmission capacity of the DN.

3. A BN-based reliability evaluation method for the radial MMG systems

The reliability evaluation of a radial MMG system needs to analyze the impact of equipment behavior on system functions and calculate the power balance between supply and demand, so it is a large computational reasoning process. Traditional reliability analysis methods cannot meet the above requirements, and a BN-based unified modeling method for performance and reliability is proposed. BN have a solid theoretical foundation and strong computational reasoning ability (Pearl, 2000) and have been applied to the reliability evaluation of complex systems (Cai et al., 2014, 2018), including power systems (Ciobanu, Munteanu, & Nemes, 2016). The biggest advantage of the BN-based method over existing methods is that it can establish a unified model of performance and reliability for MMG systems. In this model, we combine the failure state of the equipment with its corresponding performance, rather than establishing the equipment performance model and the two-state reliability model separately as in the existing methods.

A BN-based reliability method mainly includes three steps, namely, BN structure modeling, BN parameter modeling, and BN inference. For radial MMG systems, a detailed flowchart, as shown in Fig. 3, is used to evaluate reliability. The method used and details in each step are also shown in Fig. 3.

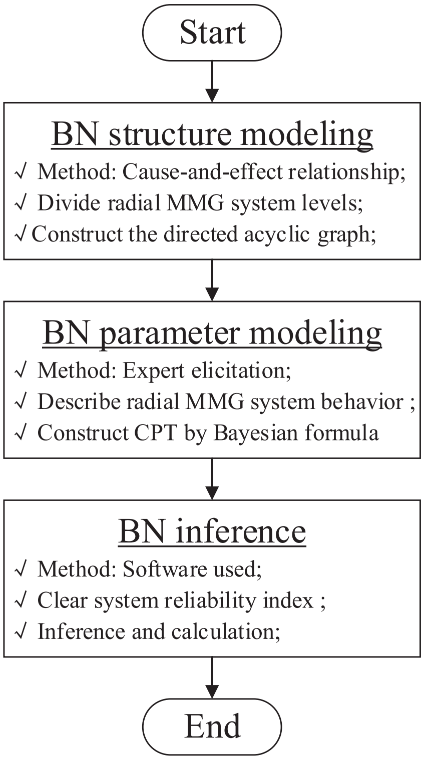

Fig. 3. The flowchart of a BN-based reliability evaluation method.

3.1. BN structure modeling

The cause-and-effect relationship methods are used to establish the system Bayesian network structure model based on the MMG operating process. First, the system is divided into four levels according to the MMG physical structure: equipment level, MG level, subsystem level and system level, which are represented by nodes respectively. It also should be noted that some transition nodes, such as node "No-sharing system n", are introduced into the model for ease of understanding and inference. Then a directed acyclic graph (DAG) is formed by connecting the nodes. Bayesian network model is shown in the following Fig. 4.

3.2. BN parameter modeling

The BN parameter model is based on its structural model. The expert elicitation methods are used to establish BN parameter model, in which the conditional probabilities of a BN for evaluation usually are specified by combining the knowledge of experts and practical experience. In this step, the system behavior is described and a system model is built. Then, the states of each node are defined, and the prior and conditional probabilities are represented by Bayesian formula based on the system model. The BN parameter model will be introduced in detail in the Section 4 due to the complexity of the system model. The state representation of the node and the meaning of the parameters are shown in Table 2.

3.3. BN inference

The Bayesian Network Toolbox in MATLAB is used for inference in this study. The system instantaneous availability is a reliability index of the radial MMG system, which is a state probability of the node "system". The system instantaneous availability can be expressed as shown in Eq. (16) in Section 4. The inference ability of the Bayesian network also reflects the ability to analyze the impact of one or more evidence variables on other nodes in the network. The impact of single microgrid island operations and bus bar connection failures on the

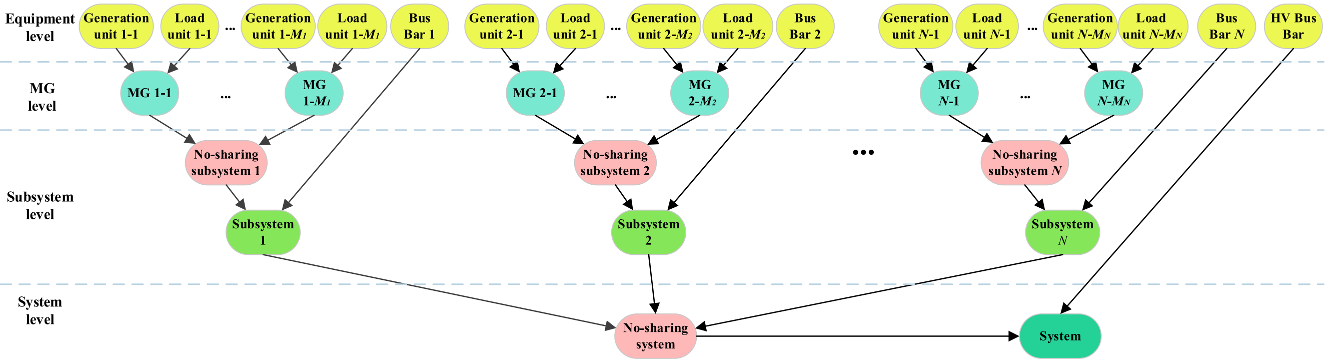

Fig. 4. Bayesian network model of a radial MMG system that oriented to performance sharing.

availability of the entire system will be analyzed in the case study.

4. The system modeling and BN parameter modeling

The system behavior modeling is the basis for establishing a BN parameter model using expert elicitation methods. The radial MMG systems model includes the dynamic behavior of equipment, the power balance of the MG, and the energy dispatch between the MGs. In this section, system behavior is mapped to each node in Fig. 4, and Bayesian formula is used to quantify the relationship between node states.

4.1. Equipment level nodes

Equipment level nodes include power generation unit, load unit, and bus bars, which are root nodes in the Bayesian network model.

The DG unit $n-m$ has K_{n-m}different performance levels. The set $\mathrm{g}_{n-m} = \{\mathrm{g}_1^{n-m}, \mathrm{g}_2^{n-m}, ..., \mathrm{g}_{k_{n-m}}^{n-m}\}$ represents the set of performance levels corresponding to the unit $n-m$ $(1 \leqslant n \leqslant N, 1 \leqslant m \leqslant M_\mathrm{n})$. For convenience of calculation, the performance levels of unit $n-m$ in this set are sorted from least to greatest, in other words, g_1^{n-m} represents the performance level when unit is in state of complete failure, and $\mathrm{g}_{k_{n-m}}^{n-m}$ represents the performance level of normal unit. $P_{n-m} = \{p_1^{n-m}(t), p_1^{n-m}(t), ..., p_{k_{n-m}}^{n-m}(t)\}$ is the set of probabilities where the unit $n-m$ corresponds to the particular performance levels. At any instant $t > 0$, the performance level $G_{n-m}(t)$ takes some value from of the set g_{n-m}. The probabilities can be expressed as follows:

$$P(G_{n-m}(t) = g_i^{n-m}) = p_i^{n-m}(t)(1 \leqslant i \leqslant K_{n-m}) \tag{1}$$

At the same time, the load unit $n-m$ has H_{n-m} demand levels. The set $\mathrm{w}_{\mathrm{n-m}} = \{w_1^{n-m}, w_2^{n-m}, ..., w_{H_{n-m}}^{n-m}\}$ (sort from least to greatest) represents the set of demand levels corresponding to the load unit $n-m$, and the set $Q_{n-m} = \{q_1^{n-m}(t), q_2^{n-m}(t), ..., q_{H_{n-m}}^{n-m}(t)\}$ contains the probabilities of the demand levels. At any instant $t > 0$, the demand level $W_{n-m}(t)$ takes some value from of the set $\mathbf{w_{n-m}}$, and the equation can be expressed as follows:

$$P(W_{n-m}(t) = w_i^{n-m}) = q_i^{n-m}(t)(1 \leqslant i \leqslant H_{n-m}) \tag{2}$$

Moreover, the bus bar n has L_n transmission levels, which are represented by the set $\mathrm{c_n} = \{c_1^n, c_2^n, ..., c_{L_n}^n\}$(sort from least to greatest). The set $\beta_n = \{\beta_1^n(t), \beta_2^n(t), ..., \beta_{L_n}^n(t)\}$ contains the probabilities of the transmission levels. At any instant $\mathrm{t} > 0$, the transmission level $C_n(t)$ takes some value from of the set $\mathrm{c_n}$, and the correspondence between the elements in the two sets is as follows:

$$P(C_n(t) = c_i^n) = \beta_i^n(t)(1 \leqslant i \leqslant L_n) \tag{3}$$

The performance of equipment in the system is multi-state, and the DSCT Markov stochastic process model describes the transition relationship among states. This process can be found in Refs (Kulkarni, 1995; Yu et al., 2014), and the performance level of the DG unit is taken as a case to explain the model. The multi-state Markov stochastic process model is shown in Fig. 5. The nodes represent the performance levels of the DG unit. Factors such as failures or ageing cause the performance level to change from the upper state l to the lower state j with the corresponding transition intensity $\lambda_{l-j}^{n-m}(1/\mathrm{h})$. Conversely, factors such as repairs cause the generation unit performance level to change from the lower state j to the upper state l with the corresponding transition intensity $\mu_{j-l}^{n-m}(1/\mathrm{h})$. The probability of the DG unit being in a performance level is a function of time, and the state probability can be solved by the following differential equation (i.e., the Chapman–Kolmogorov equation):

$$\begin{cases} \frac{dp_1^{n-m}(t)}{dt} = \sum_{l=2}^{K_{n-m}} \lambda_{l-1}^{n-m} p_l^{n-m}(t) - p_1^{n-m}(t) \sum_{l=2}^{K_{n-m}} \mu_{1-l}^{n-m} \\ \frac{dp_j^{n-m}(t)}{dt} = \sum_{l=j+1}^{K_{n-m}} \lambda_{l-j}^{n-m} p_l^{n-m}(t) + \sum_{l=1}^{j-1} \mu_{l-j}^{n-m} p_l^{n-m}(t) \\ \qquad - p_j^{n-m}(t)\left(\sum_{l=1}^{j-1} \lambda_{j-l}^{n-m} + \sum_{l=j+1}^{K_{n-m}} \mu_{j-l}^{n-m}\right), (l < j < K_{n-m}) \\ \frac{dp_{K_{n-m}}^{n-m}(t)}{dt} = \sum_{l=1}^{K_{n-m}-1} \mu_{l-K_{n-m}}^{n-m} p_l^{n-m}(t) - p_{K_{n-m}}^{n-m}(t) \sum_{l=1}^{K_{n-m}-1} \lambda_{K_{n-m}-l}^{n-m} \end{cases} \tag{4}$$

Table 2
Node state representation and parameter meaning.

Node	State representation	Unit	Parameter meaning
Generation unit *n-m*	$G_{n-m}(t)$	W	DG unit *n-m* performance levels
Load unit *n-m*	$W_{n-m}(t)$	W	Load unit *n-m* demand levels
Bus bar *n*	$C_n(t)$	W	bus bar *n* transmission levels
MG *n-m*	$(S_{n-m}(t), D_{n-m}(t))$	(W,W)	MG *n-m* surplus performance and deficiency performance
No-sharing subsystem *n*	$(S_n(t), D_n(t))$	(W,W)	Subsystem *n* surplus performance and deficiency performance before power exchanges
Subsystem *n*	$S_n'(\mathrm{t}), D_n'(\mathrm{t})$) or Unavailable Subsystem n	(W,W)/–	Subsystem *n* surplus performance and deficiency performance
No-sharing system	$S(t), D(t)$ or *Unavailable No − sharing System*	(W,W)/–	System surplus performance and deficiency performance before power exchanges
system	*Available System* or *Unavailable System*	–	System state

Note: n is the number of the subsystem($n = 1, 2, …, \mathrm{N}$); m is the number of the MG ($m = 1,2, …, M_n$).

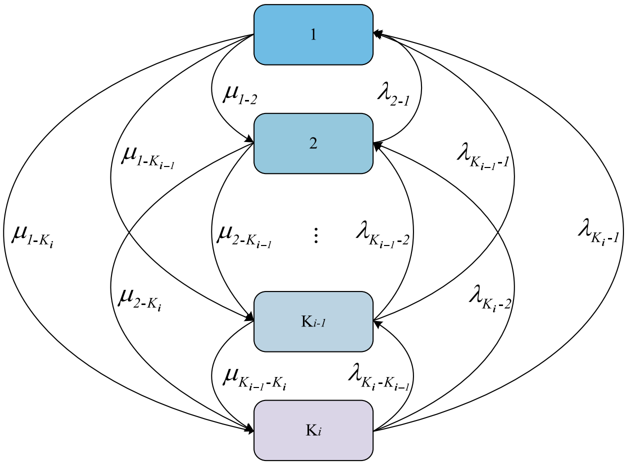

Fig. 5. Multi-state Markov stochastic process model.

4.2. MG level nodes

According to the energy dispatch strategy, the MG preferentially satisfies its own demand; thus, the MG has a power state at every moment. If the performance level is greater than the demand level, then the MG has surplus performance; otherwise, the MG is in a performance deficiency state. At any instant t>0, the total surplus performance and performance deficiency of the MG $n-m$ can be written as:

$$\begin{cases} S_{n-m}(t) = \max(G_{n-m}(t) - W_{n-m}(t), 0) \\ D_{n-m}(t) = \max(W_{n-m}(t) - G_{n-m}(t), 0) \end{cases} \tag{5}$$

In BN model, with a known performance level $G_{n-m}(t)$, demand level $W_{n-m}(t)$, $(S_{n-m}(t), D_{n-m}(t))$ is uniquely determined. When their relationships satisfy Equation (5), the relationships can be expressed by the following Bayesian formula, namely, the parameter model of the nodes "MG$n-m$" is obtained.

$$p\{(S_{n-m}(t), D_{n-m}(t))|G_{n-m}(t) = g_i^{n-m}, W_{n-m}(t) = w_j^{n-m}\} = 1 \tag{6}$$

Table 4
Transition intensities and demand levels of the loads.

Load demand		Transition intensities (1/day)			Demand (MW)	Initial conditions
Load	Level	L1	L2	L3		
1-1	L1	−0.006	0	0.006	0	0
	L2	0	−0.012	0.012	2	1
	L3	0.008	0.015	−0.023	3	0
1-2	L1	−0.001	0.001	–	0	0
	L2	0.002	−0.002	–	2	1
1-3	L1	−0.03	0	0.03	0	0
	L2	0	−0.06	0.06	3	1
	L3	0.04	0.05	−0.09	4	0
2-1	L1	−0.001	0.001	–	0	1
	L2	0.002	−0.002	–	2	0
2-2	L1	−0.005	0	0.005	0	0
	L2	0	−0.006	0.006	2	1
	L3	0.004	0.005	−0.009	3	0
2-3	L1	−0.005	0	0.005	0	0
	L2	0	−0.01	0.01	2	1
	L3	0.01	0.015	−0.025	3	0
3-1	L1	−0.008	0	0.008	0	0
	L2	0	−0.015	0.015	2	0
	L3	0.01	0.02	−0.03	3	1
3-2	L1	−0.001	0.001	–	0	1
	L2	0.002	−0.002	–	3	0
3-3	L1	−0.004	0	0.004	0	0
	L2	0	−0.009	0.009	3	1
	L3	0.008	0.012	−0.02	4	0

4.3. Subsystem level nodes

Transition nodes "*No-sharing subsystem n*" were introduced for modeling. Assuming that performance is not transferred among MGs, all surplus performances of subsystem n can be expressed as follows:

$$S_n(t) = \sum_{m=1}^{M_n} S_{n-m}(t) = \sum_{m=1}^{M_n} (\max(G_{n-m}(t) - W_{n-m}(t), 0)) \tag{7}$$

Moreover, all deficiency performances can be written as follows:

Table 3
Transition intensities and performance levels of the DG units.

DGs performance		Transition intensities (1/day)			Performance (MW)	Initial conditions
DG	Level	L1	L2	L3		
1-1	L1	−0.060	0	0.060	0	0
	L2	0	−0.018	0.018	2	0
	L3	0.012	0.016	−0.028	3	1
1-2	L1	−0.080	0	0.080	0	0
	L2	0	−0.024	0.024	3	0
	L3	0.010	0.035	−0.045	4	1
1-3	L1	−0.010	0.010	–	0	0
	L2	0.001	−0.001	–	3	1
2-1	L1	−0.010	0.010	–	0	0
	L2	0.001	−0.001	–	2	1
2-2	L1	−0.090	0	0.090	0	0
	L2	0	−0.025	0.025	3	0
	L3	0.01	0.020	−0.03	4	1
2-3	L1	−0.050	0	0.050	0	0
	L2	0	−0.020	0.02	2	0
	L3	0.010	0.018	−0.028	4	1
3-1	L1	−0.080	0	0.080	0	0
	L2	0	−0.025	0.025	3	0
	L3	0.012	0.030	−0.042	5	1
3-2	L1	−0.010	0.010	–	0	0
	L2	0.001	−0.001	–	2	1
3-3	L1	−0.070	0	0.070	0	0
	L2	0	−0.018	0.018	3	0
	L3	0.020	0.026	−0.046	4	1

Table 5
Transition intensities and transmission capacities of the bus bar.

Bus bar		Transition intensities (1/day)			Transmission capacity (MW)	Initial conditions
Bus bar	Level	L1	L2	L3		
1	L1	−0.500	0.500	–	0	0
	L2	0.005	−0.005	–	4	1
2	L1	−0.500	0.500	–	0	1
	L2	0.005	−0.005	–	4	0
3	L1	−0.500	0.500	–	0	0
	L2	0.005	−0.005	–	4	1
HV Bus bar	L1	−0.100	0	0.100	0	0
	L2	0.002	−0.202	0.200	5	0
	L3	0	0.002	−0.002	6	1

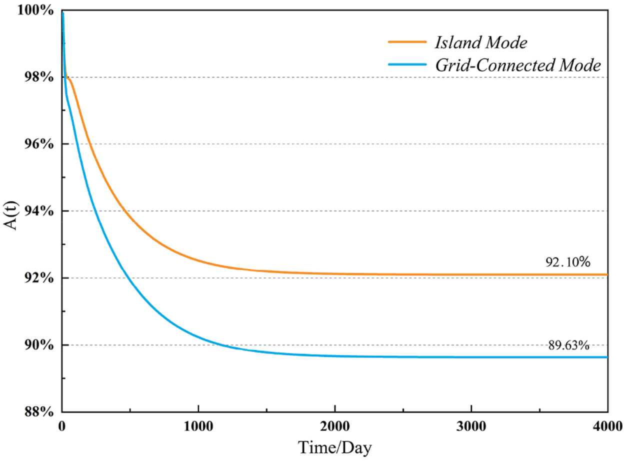

Fig. 6. Instantaneous availability of the radial MMG system.

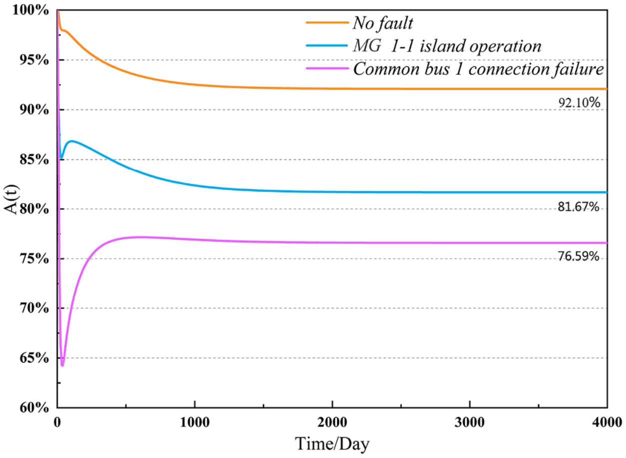

Fig. 7. Instantaneous availability of the radial MMG system in island mode.

$$D_n(t) = \sum_{m=1}^{M_n} D_{n-m}(t) = \sum_{m=1}^{M_n} (max(W_{n-m}(t) - G_{n-m}(t), 0)) \tag{8}$$

The parameter model of the nodes “No-sharing subsystem n” can be expressed as:

$$p\{[S_n(t), D_n(t)]|[S_{n-1}(t), D_{n-1}(t)], [S_{n-2}(t), D_{n-2}(t)], ...,[S_{n-M_n}(t), D_{n-M_n}(t)]\} = 1 \tag{9}$$

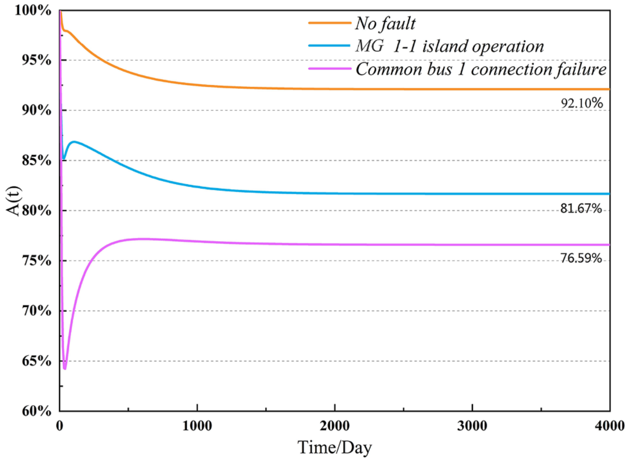

Fig. 8. Instantaneous availability of the radial MMG system in grid-connected mode.

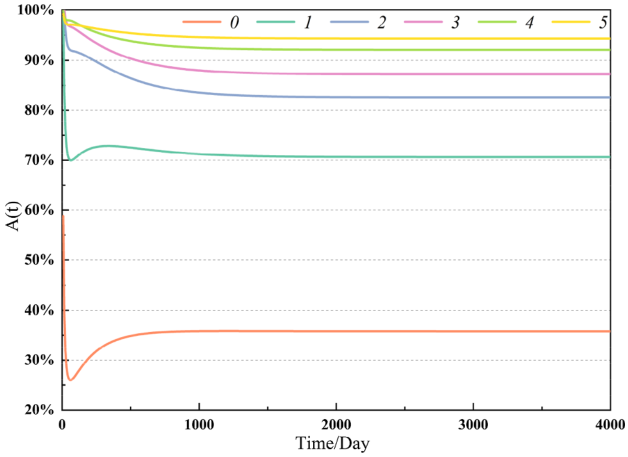

Fig. 9. Impact of distribution network transmission capacity on system availability in grid-connected mode.

The surplus performance will be transmitted to nearest performance-deficient MGs, and the total transmitted power cannot exceed the capacity of the DN. Assuming that the performance of the utility grid and other subsystems is not transmitted to subsystem n, if the performance deficiency is greater than the transmission capacity, the demand of the loads in this subsystem cannot be satisfied, which will cause the system to be failure. In the node “subsystem n”, this state is defined as “Unavailable Subsystem n”. If not, the subsystem will have surplus performance or need to be offered performance within a controllable range. The subsystem state after first performance sharing is represented by an array($S_n'(t)$, $D_n'(t)$) or “Unavailable Subsystem”; this process can be represented by Algorithm 1.

Algorithm 1:.

```
if $D_n(t) > C_n(t)$
  Unavailable Subsystem n;
else if $S_n(t) > D_n(t)$
    $S'_n(t) = \min(S_n(t), C_n(t)) - D_n(t),\ D'_n(t) = 0$;
  else
    $D'_n(t) = D_n(t) - S_n(t),\ S'_n(t) = 0$;
  end
end
```

In BN model, when the state of node “No-sharing subsystem *n*”, the transmission capacity of distribution network *n* and the state of node “Subsystem *n*” meet the one-to-one correspondence defined by Algorithm 1, the following Bayesian formula will be established, and the parameter model of the nodes “Subsystem *n*” is obtained.

$$p\{(S'_n(t), D'_n(t))/Unavailable\ Subsystem\ n|(S_n(t), D_n(t)), C_n(t)\} = 1 \tag{10}$$

4.4. System level nodes

Similarly, the transition node “No-sharing system” was introduced. It is obvious that the system is not available when any subsystem is in state of “Unavailable Subsystem*n*”, which is recorded as “Unavailable No-Sharing System” state in node “No-Sharing System”.

Assuming that the surplus performance of the subsystem is not shared by the distribution network, the surplus performance of all subsystems can be expressed as follows:

$$S(t) = \sum_{n=1}^{N} S'_n(t) \tag{11}$$

Similarly, the performance deficiency of all subsystems can be expressed as follows:

$$D(t) = \sum_{n=1}^{N} D'_n(t) \tag{12}$$

The parameter model of the node “No-Sharing System” can be expressed by the Bayesian formula as:

$$\begin{cases} p\{Unavailable\ No-sharing\ System| \\ \qquad\qquad \exists\ Unavailable\ Subsystem\} = 1 \\ p\{(S(t), D(t))|(S'_1(t), D'_1(t)), (S'_2(t), D'_2(t)), \\ \qquad\qquad \ldots, (S'_N(t), D'_N(t))\} = 1 \end{cases} \tag{13}$$

When the system is in island mode, only the surplus performance of the subsystem can be shared, and it cannot exceed the capacity of the HV distribution network. If the performance that can be shared ($\min(S(t), C(t))$) is greater than the performance deficiency of all subsystems, the system is available; otherwise, unavailable. In grid-connected mode, the utility grid supplies continuous performance for the system. The maximum performance that can be shared is the capacity of HV distribution network. If the performance deficiency of all subsystems is less than the transmission level of HV distribution network, the system is available; otherwise, unavailable. The process is expressed as Algorithm 2.

Algorithm 2:.

```
Island mode:
if ∃ UnavailableNo − SharingSystem
  Unavailable System;
else if $\min(S(t), C(t)) < D(t)$
    Unavailable System;
  else
    Available System;
  end
end
Grid − connected mode:
if ∃ UnavailableNo − SharingSystem
  Unavailable System;
else if $C(t) < D(t)$
    Unavailable System;
  else
    Available System;
  end
end
```

The reliability evaluations of the island mode and the grid-connected mode are different. When the system is in island mode, the parameter model of the node “System” can be expressed as:

$$\begin{cases} p\{Unavailable\ System|\ \exists\ Unavailable\ No-sharing\ System\} = 1 \\ p\{Unavailable\ System|\min(S(t), C(t)) < D(t)\} = 1 \\ p\{Available\ System|\min(S(t), C(t)) \geqslant D(t)\} = 1 \end{cases} \tag{14}$$

In grid-connected mode, it can be written as follows:

$$\begin{cases} p\{Unavailable\ System|\ \exists\ Unavailable\ No-sharing\ System\} = 1 \\ p\{Unavailable\ System|C(t) < D(t)\} = 1 \\ p\{Available\ System|C(t) \geqslant D(t)\} = 1 \end{cases} \tag{15}$$

At any instant $t > 0$, the *instantaneous availability* of the system is defined as the probability that all the MGs satisfy the demands. The Bayesian network can infer the probability that the node “System” is in the state “Available system”, which is the instantaneous availability of the system and can be written as follows:

$$A(t) = p(Available\ System) \tag{16}$$

The BN-based unified model of performance and reliability is established, which is not only applicable to the reliability evaluation of the MMG, but also to performance sharing systems.

5. Case study

5.1. Input data

The case model is derived from the single-phase roadway radial MMG system model in Ref (Jiao & Qiao, 2013). This case is a simplified model, only for verification. The case consists of three subsystems each containing three MGs. Table 3 provides information on the performance level, conversion strength, and initial performance level of each DG units in the region. Table 4 provides information on the demand level, conversion strength, and initial demand level of each load. Table 5 shows information on the transmission level, conversion strength, and initial capacity of the bus bars.

5.2. Results and analysis

Based on the method proposed above and the given data, reliability evaluation was performed using the Bayesian Network Toolbox in MATLAB.

The reliability evaluation results are as follows: Fig. 6 shows the availability of the radial MMG system (island and grid-connected modes) over time. When in island mode, the availability first decreases rapidly with time and then changes to be steady. The availability of island mode is 89.63%, when the system is stable. The Grid-connected mode has a similar trend. When the system in grid-connected mode is stable, the availability is 92.10%, which is slightly higher than that in island mode. Comparing the instantaneous availability of two modes, it is obvious that grid-connected mode has a higher availability than island mode. When in grid-connected mode, the utility grid provides a continuous supply of power performance for the MMGs, which can improve the availability of the system. When the system is in steady state, the availability of the two modes differs by only 1.28%, which indicates that the MMG system is highly self-sufficient.

5.3. Dynamic reliability analysis using the fault injection method

The dynamic reliability of MMGs will be studied using the fault injection method. This section considers two faults. For the first one, a single MG is not connected to the MMG system and is in island mode; this fault is called single MG island mode. For the second one, the MV bus bar of the subsystem is not connected to the HV bus bar, and the entire subsystem is in island mode; this fault is called bus bar connection failure.

Next, the calculation of system availability will be described after fault injection. When a single MG is in island mode, system availability is expressed as the product of the MMG system availability without the corresponding MG and the availability of the corresponding MG. Similarly, when the bus bar is in connection failure, system availability is expressed as the product of the system availability that does not include the corresponding subsystem and the availability of the corresponding subsystem. The two faults injected in this case are MG 1-1 island mode and MV bus bar 1 connection failure.

Fig. 7 is a graph showing the availability of the system over time after failure injection in island mode. When MG 1-1 is in island mode, the availability of the system drops sharply at first, and then gradually increases until it is finally stable. The availability of the system at steady state is 73.68%, which is 15.95% lower than the availability of the system without faults. The drastic reduction in system availability occurs because the independently operating MG 1-1 availability is only 82.11%, which reduces the availability of the entire system. When MV bus bar 1 is in connection failure, there is a complex trend in system availability over time: first, the availability rapidly declines, then it increases, and then it slowly declines again until it is finally stable. The availability is 79.31% when the system is stable, which is 10.32% lower than the availability of the system without faults. When the bus bar is in connection failure, the performance can be shared only within a limited range rather than throughout the entire system, which constrains system availability.

The availability curve of the system, which is in grid-connected mode, after failure injection, is shown in Fig. 8. The trend of availability is similar to that in island mode. When the system is stable, the system availability of MG 1-1, which operates independently, is 76.59%, which is 15.51% lower than the availability of the system without faults. The system availability is 81.67% when MV bus bar 1 is in connection failure, which is 10.43% lower than that in the system without faults. The comparison shows that the impact of faults on the availability of the system is smaller in grid-connected mode than in island mode. It can be seen that the utility grid guarantees the availability of the entire system.

5.4. Sensitivity analysis

The transmission capacity of the bus bar will constrain the sharing of power performance, further affecting the reliability of the system. MV bus bar 1, as an example, is used to analyze the impact of transmission capacity on system reliability in this section.

The transmission capacity of MV bus bar 1 is set to six levels (0, 1 MW, •••, 5 MW). Fig. 9 shows the impact of transmission capacity on system availability. It can be concluded that as transmission capacity increases, the instantaneous availability of the system increases when the system is in a steady state. Because the increase in transmission capacity allows more power performance to be shared to satisfy the demands of different MGs. However, the increase in availability has gradually decreased, so the method of increasing the transmission capacity can compensate for the system unavailability caused by the low probability extreme events limitedly. Bayesian network reverse reasoning can identify weak points in the system, which can guide the design of the MMG to make the system more reliable.

6. Conclusion

With more and more MGs interconnected to the DN, a radial MMG system will be formed in a wide area. In this study, the radial MMG system is abstracted into a performance-sharing system, and a BN-based reliability evaluation analytical method is proposed. In this method, a unified model of performance and reliability of the radial MMG system is established, which takes into account the equipment partial failure and incomplete maintenance, as well as capacity constraints of the DN. The analytical method can quickly evaluate and analyze system reliability and will play a guiding role in the design, operation and maintenance of the radial MMG systems and general performance sharing system.

Energy storage and energy dispatch strategy optimization have emerged as one of the key issues in the reliability evaluation of MMG systems. In addition, common causes of failure and cascading failures of electrical equipment will be considered in the future.

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References

Arefifar, S. A., Mohamed, Y. A. I., & Elfouly, T. H. M. (2013). Optimum microgrid design for enhancing reliability and supply-security. *IEEE Transactions on Smart Grid, 4*(3), 1567–1575.

Bae, I., & Kim, J. (2008). Reliability evaluation of customers in a microgrid. *IEEE Transactions on Power Systems, 23*(3), 1416–1422.

Bai, H., Miao, S., Zhang, P., & Bai, Z. (2015). Reliability evaluation of a distribution network with microgrid based on a combined power generation system. *Energies, 8*(2), 1216–1241.

Bie, Z., Zhang, P., Li, G., Hua, B., Meehan, M., & Wang, X. (2012). Reliability evaluation of active distribution systems including microgrids. *IEEE Transactions on Power Systems, 27*(4), 2342–2350.

Cai, B., Kong, X., Liu, Y., Lin, J., Yuan, X., Xu, H., & Ji, R. (2018). Application of bayesian networks in reliability evaluation. *IEEE Transactions on Industrial Informatics* 1–1.

Cai, B., Liu, Y., Fan, Q., Zhang, Y., Liu, Z., Yu, S., & Ji, R. (2014). Multi-source information fusion based fault diagnosis of ground-source heat pump using Bayesian network. *Applied Energy, 114*, 1–9.

Ciobanu, A., Munteanu, F., & Nemes, C. (2016). Bayesian networks utilization for reliability evaluation of power systems. *Proceedings of the 2016 international conference and exposition on electrical and power engineering (Epe 2016)* (pp. 837–841). IEEE.

Conti, S., Nicolosi, R., & Rizzo, S. A. (2012). Generalized systematic approach to assess distribution system reliability with renewable distributed generators and microgrids. *IEEE Transactions on Power Delivery, 27*(1), 261–270.

Conti, S., Rizzo, S. A., El-Saadany, E. F., Essam, M., & Atwa, Y. M. (2014). Reliability assessment of distribution systems considering telecontrolled switches and microgrids. *IEEE Transactions on Power Systems, 29*(2), 598–607.

Costa, P. M., & Matos, M. A. (2009). Assessing the contribution of microgrids to the reliability of distribution networks. *Electric Power Systems Research, 79*(2), 382–389.

Farzin, H., Fotuhi-Firuzabad, M., & Moeini-Aghtaie, M. (2017). Reliability studies of modern distribution systems integrated with renewable generation and parking lots. *IEEE Transactions on Sustainable Energy, 8*(1), 431–440.

Farzin, H., Fotuhi-Firuzabad, M., & Moeini-Aghtaie, M. (2018). Role of outage management strategy in reliability performance of multi-microgrid distribution systems. *IEEE Transactions on Power Systems, 33*(3), 2359–2369.

Gazijahani, F. S., & Salehi, J. (2018). Reliability constrained two-stage optimization of multiple renewable-based microgrids incorporating critical energy peak pricing demand response program using robust optimization approach. *Energy, 161*, 999–1015.

Gil, N. J., & Lopes, J. A. P. (2007). Hierarchical frequency control scheme for islanded multi-microgrids operation. *2007 IEEE Lausanne Power Tech,* 473–478.

Hemmati, M., Amjady, N., & Ehsan, M. (2014). System modeling and optimization for islanded micro-grid using multi-cross learning-based chaotic differential evolution algorithm. *International Journal of Electrical Power & Energy Systems, 56*, 349–360.

Jia, H., Ding, Y., Peng, R., & Song, Y. (2017). Reliability evaluation for demand-based warm standby systems considering degradation process. *IEEE Transactions on Reliability, 66*(3), 795–805.

Jiao, Y., & Qiao, W. (2013). A hierarchical power management strategy for multiple single-phase roadway microgrids. *2013 IEEE Power & Energy Society General Meeting*. IEEE.

Kulkarni, V. G. (1995). *Modeling and analysis of stochastic systems*. USA: Chapman & Hall189–203.

Levitin, G. (2011). Reliability of multi-state systems with common bus performance sharing. *IIE Transactions, 43*(7), 518–524.

Levitin, G., Xing, L., & Huang, H. (2019). Dynamic availability and performance deficiency of common bus systems with imperfectly repairable components. *Reliability Engineering & System Safety, 189*, 58–66.

Lisnianski, A., & Ding, Y. (2009). Redundancy analysis for repairable multi-state system by using combined stochastic processes methods and universal generating function technique. *Reliability Engineering & System Safety, 94*(11), 1788–1795.

Madureira, A. G., Pereira, J. C., Gil, N. J., Lopes, J. A. P., Korres, G. N., & Hatziargyriou, N. D. (2011). Advanced control and management functionalities for multi-microgrids. *European Transactions on Electrical Power, 21*(2), 1159–1177.

Moslehi, K., & Kumar, R. (2010). A Reliability perspective of the smart grid. *IEEE Transactions on Smart Grid, 1*(1), 57–64.

Nikmehr, N., & Najafi-Ravadanegh, S. (2015). Reliability evaluation in multi-microgrids under probabilistic optimum operation using heuristic algorithm. *2015 Smart Grid Conference (SGC)* (pp. 92–98). IEEE.

Nikmehr, N., & Najafi-Ravadanegh, S. (2016). Reliability evaluation of multi-microgrids considering optimal operation of small scale energy zones under load-generation uncertainties. *International Journal of Electrical Power & Energy Systems, 78*, 80–87.

Pearl, J. (2000). *Causality: Models, Reasoning, and Inference*. USA: Cambridge University Press.

Peng, R., Liu, H., & Xie, M. (2016). A study of reliability of multi-state systems with two performance sharing groups. *Quality and Reliability Engineering International, 32*(7), 2623–2632.

Peng, R., Xiao, H., & Liu, H. (2017). Reliability of multi-state systems with a performance sharing group of limited size. *Reliability Engineering & System Safety,* 164–170.

Qiu, S., & Ming, H. X. (2019). Reliability evaluation of multi-state series-parallel systems with common bus performance sharing considering transmission loss. *Reliability Engineering & System Safety, 189*, 406–415.

Zhang, X., Su, X., Cheng, Y., & Wei, C. (2017). A novel multi-microgrids system reliability assessment algorithm using parallel computing. *Ieee conference energy internet and energy system integration* (pp. 1–5). IEEE.

Wang, S., Zhang, X., Wu, L., & Sun, S. (2018). New metrics for assessing the performance of multi-microgrid systems in stand-alone mode. *International Journal of Electrical Power & Energy Systems, 98*, 382–388.

Xiao, H., & Peng, R. (2014). Optimal allocation and maintenance of multi-state elements in series–parallel systems with common bus performance sharing. *Computers & Industrial Engineering, 72*, 143–151.

Xu, Z., Yang, P., Zheng, C., Zhang, Y., Peng, J., & Zeng, Z. (2018). Analysis on the organization and development of multi-microgrids. *Renewable & Sustainable Energy Reviews, 81*, 2204–2216.

Yu, H., Yang, J., Lin, J., & Zhao, Y. (2017). Reliability evaluation of non-repairable phased-mission common bus systems with common cause failures. *Computers & Industrial Engineering, 111*, 445–457.

Yu, H., Yang, J., & Mo, H. (2014). Reliability analysis of repairable multi-state system with common bus performance sharing. *Reliability Engineering & System Safety, 132*, 90–96.

Yu, H., Yang, J., & Zhao, Y. (2018). Reliability of nonrepairable phased-mission systems with common bus performance sharing. *Proceedings of the Institution of Mechanical Engineers Part O-Journal of Risk and Reliability, 232*(6), 647–660.

Zhao, X., Wu, C., Wang, S., & Wang, X. (2018). Reliability analysis of multi-state k-out-of-n: G system with common bus performance sharing. *Computers & Industrial Engineering, 124*, 359–369.