Multi-state time-varying reliability evaluation of smart grid with flexible demand resources utilizing $L_z$ transform

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Abstract. With the expanding proportion of renewable energy generation and development of smart grid technologies, flexible demand resources (FDRs) have been utilized as an approach to accommodating renewable energies. However, multiple uncertainties of FDRs may influence reliable and secure operation of smart grid. Multi-state reliability models for a single FDR and aggregating FDRs have been proposed in this paper with regard to responsive abilities for FDRs and random failures for both FDR devices and information system. The proposed reliability evaluation technique is based on $L_z$ transform method which can formulate time-varying reliability indices. A modified IEEE-RTS has been utilized as an illustration of the proposed technique.

1. Introduction

With the rising challenges of conventional energy crisis and environmental pollutions, the utilization of renewable energies has been rapidly expanding in the last decades [1]. The proportion of installed capacity for renewable energy will continue growing in the years to come [2]. However, renewable energies differ from other traditional power generation methods mainly in its natures of randomicity, intermittence and fluctuation [3,4]. In order to ensure the secure and reliable operation of power systems, some rapid start-up conventional generating units, such as thermal power units, are necessary for accommodating renewable energy [5]. Nevertheless, these techniques may increase operation and maintenance cost as well as greenhouse gases emissions [6].

Nowadays, the development of demand response has not only made better integration of renewable energy but also increased efficiency of power systems [7,8]. In this paper, flexible demand resources (FDRs) are defined as some dispatch-able devices in electric utilization by consumers whose power capacities can be actively participated to achieve demand response [9,10]. Some general components of FDR including electrical vehicles, heat pumps, air conditioners and distributed generations have been utilized to realize bidirectional interaction between electric power providers and electric power consumers in smart grid [11,12]. The potentials of FDRs for different scenarios have been studied in recent years [13,14]. The utilization of FDRs can contribute to more than 20% peak demand reduction [15].

However, the multiple uncertainties from internal and external factors of FRPs make great influences on power system in term of reliability and security. External uncertainties such as weather and operating conditions, internal uncertainties such as random failures and response degree of FDR devices to price signals, incentive mechanisms and dispatch commands are supposed to have significant effects on the operation of FDRs. Furthermore, with the development of cyber physical
systems (CPS) [16], the active participations of FDRs are more dependent on information systems. Accordingly, the vulnerability of CPS affects the involvement of FDRs in smart grid [16]. Therefore, in order to achieve reliable operation and effective management of power systems, it is essential to carry out reliability evaluation of FDRs with regard to growing uncertainties.

Extensive researches for reliability assessment of generation, transmission and distribution systems have gained certain progress [17]. However, the reliability model focused on demand side gets relatively less attention [18-20]. The reliability models of consumers in demand side are more related to simulation techniques which only provide inaccurate results [18, 21]. Analytical approaches of reliability such as universal generating function (UGF) have been utilized in power systems with high wind power penetration [22, 23]. The UGF methods can deal with reliability evaluation for the system to overcome the curse of dimensionality compared with state-space based method such as Markov process model and reduce the computational burden. Whereas, UGF methods consider the capacities and probabilities of components as random variables instead of time-varying variables [24]. The general definitions for Lz transform approaches have been proposed in [25] to overcome the shortcomings. Lz transform methods have been formulated in availability evaluation for refrigeration system [26] and water cooling system [27]. In these presented articles, multi-state time-vary reliability models of FDRs are proposed utilizing Lz transform techniques which are extended from UGF methods.

The rest of the paper is organized as follows. Section 2 illustrates multi-state reliability model for a single FDR device in term of potential capacity and random failures. Reliability model of aggregation for multiple FDRs utilizing Lz transform technique is formulated in Section 3. The IEEE RTS [28] is modified to depict the validity and benefits of the proposed approach in Section 4. Section 5 gives the conclusions.

2. Multi-state reliability model for a single FDR device

The power capacity of a FDR at time $t$ is determined by the availability of the FDR at that time. Multi-state model can be utilized to illustrate power capacity of FDR considering potential of FDR and random failures. The corresponding Lz transform to describe the potential of FDR $k$ at bus $i$ can be defined as

$$Lz^f_{ik}(z,t) = \sum_{j_{ik}=1}^{K_{ik}} p^f_{j_{ik}}(t) \cdot z^{f_{j_{ik}}},$$

where $p^f_{j_{ik}}(t)$ and $f_{j_{ik}}$ are the time-varying probability at time $t$ and the power capacity of FDR $k$ for the state $j_{ik}$ at bus $i$, respectively. $K_{ik}$ is the state number for FDRs at bus $i$. $Lz^f_{ik}(z,t)$ describes the potential distribution for FDR $k$. $z$ indicates the Lz transform for a discrete random variable with its state performances and corresponding state probabilities.

The power capacity of a FDR is also determined by its reliability considering random failures of itself and information system. The power capacity is $f_{ik}$ when the FDR in operating state. The reliability model of FDR in terms of random failures is utilized by a two-state model. The Lz transform of the capacity for FDR $k$ at bus $i$ can be defined as

$$Lz^r_{ik}(z,t) = \left(1 - up^r_{j_{ik}}(t)\right) \cdot z^{f_{j_{ik}}} + up^r_{j_{ik}}(t) \cdot z^0$$

where $up^r_{j_{ik}}(t)$ represents the time-varying failure probabilities of FDR $k$ and information system at bus $i$.

The multi-state power capacity model of a FDR considering both the potential of FDR and random failures can be obtained by combining (1) and (2). The Lz transform for FDR $k$ at bus $i$ in terms of both potentials and reliability of FDR can be calculated utilizing universal generating operator (UGO) $\otimes_{ser}$ for multi-state component in series.
3. Multi-state reliability model of aggregation for multiple FDRs

The power capacity of an individual FDR is limited and the aggregation of multiple FDRs is needed for providing the necessary power system reserves. The reliability model of multiple FDRs after aggregation is illustrated in Figure 1.

\[ L_{Z_{\text{par}}}^d(z,t) = \bigotimes_{\text{par}} \left\{ L_{Z_{\text{fdr}}}^d(z,t), \cdots, L_{Z_{\text{fdr}}}^d(z,t), \cdots, L_{Z_{\text{fdr}}}^d(z,t) \right\} \]

\[ = \bigotimes_{\text{par}} \left\{ \sum_{j_{a1}=1}^{K_{a1}} p_{j_{a1}}^f(t) \cdot \left[ (1 - up_{j_{a1}}^{re}(t))z^{f_{j_{a1}}^{I_{a1}}} + up_{j_{a1}}^{re}(t)z^0 \right], \cdots, \sum_{j_{aI}=1}^{K_{aI}} p_{j_{aI}}^f(t) \cdot \left[ (1 - up_{j_{aI}}^{re}(t))z^{f_{j_{aI}}^{I_{a1}}} + up_{j_{aI}}^{re}(t)z^0 \right] \right\} \]

\[ = \sum_{j_{a1}=1}^{K_{a1}} \cdots \sum_{j_{aI}=1}^{K_{aI}} p_{j_{a1}}^f(t) \cdots p_{j_{aI}}^f(t) \cdot \left[ \prod_{k=1}^{n} (1 - up_{j_{a1}}^{re}(t))z^{\sum_{i=1}^{K_{aI}} f_{j_{aI}}^{I_{a1}}} + \cdots + \prod_{k=1}^{n} up_{j_{aI}}^{re}(t)z^0 \right] \]

\[ = \sum_{j_{a1}=1}^{K_{a1}} \cdots \sum_{j_{aI}=1}^{K_{aI}} p_{j_{a1}}^f(t) \cdots p_{j_{aI}}^f(t) \cdot z^{f_{j_{a1}}^{I_{a1}}} \]

where \( p_{j_{a1}}^f(t) \) and \( f_{j_{a1}}^{I_{a1}} \) are the time-varying probabilities and power capacities of aggregating FDRs at bus \( i \) for state \( j_{a1} \), respectively. \( K_{a1} \) represents the number of states for aggregating FDRs at bus \( i \).
Considering the strong correlation of the FDRs in the same type, the multiple states of aggregation for each type can be obtained by summing up the power capacities for the same type of FDRs:

\[ f_{d,j} = \sum_{k=1}^{n_k} f_{k,j} \]  

where \( f_{d,j} \) represents the power capacity in state \( j_m \) for aggregation of type \( m \) at bus \( i \). \( f_{k,j} \) indicates the power capacity of FDR \( k \) in state \( j_m \).

The \( L_z \) transform for \( n_m \) FDRs after aggregation can be expressed as:

\[ L_{z_{im}}(z, t) = \sum_{j=1}^{K_m} p'_{j_m}(t) \cdot z^{j_{im}} = \sum_{j=1}^{K_m} p'_{j_m}(t) \cdot z^{j_{im}} \]  

where \( p'_{j_m}(t) \) represents the time-varying probabilities of the power capacity of aggregating FDR for the state \( j_m \) at bus \( i \). \( K_m \) is the number of states for aggregating FDRs.

4. Reliability indices

In order to obtain reliability indices of the systems, the reliability model for conventional generator in [22] is utilized. Reliability indices such as instantaneous availability (IA), expected instantaneous performance (EIP), expected instantaneous performance deficiency (EIPD) and expected energy not supplied (EENS) are formulated in this paper to achieve reliability evaluation for power systems.

\[ IA(t) = \sum_{j=1}^{K_m} p_j(t) \quad (L_j \leq G_j) \]  

\[ EIP(t) = \sum_{j=1}^{K_m} G_j(t) \cdot p_j(t) \]  

\[ EIPD(t) = \sum_{j=1}^{K_m} (L_j(t) - G_j(t)) \cdot p_j(t) \quad (L_j > G_j) \]  

\[ EENS(t) = \int_0^t \left( \sum_{j=1}^{K_m} p_j(t) \cdot (L_j(t) - G_j(t)) \right) \cdot dt \quad (L_j > G_j) \]

In (7), (8), (9) and (10), \( L_j \) and \( G_j \) denote load and generation of the system in state \( j \), respectively.

5. System studies

The modified IEEE-RTS [28] has been utilized to illustrate the reliability model of FDRs. Considering the effects of FDRs in term of accommodating high penetration wind power, a large wind farm with 300 identical 2-MW wind turbine generators is added to the system. The characteristics of the wind turbine generators are represented as multi-state models [29]. The power output and state probability of a wind turbine generator developed in [29] are utilized in this case study. There are four identical 575-MW coal thermal generating units [30] and three 197-MW oil thermal generating units [28] installed in this system. It is assumed that there are 200000 FDRs distributed in the system which can be aggregated to 200 clusters. The state-space diagram for a general FDR is depicted in Figure 2. The state transition rates between two states are shown in Table I. The mean time to failure (MTTF) and mean time to repair (MTTR) of FDR are assumed to be 3650 hours and 50 hours, respectively.

There are two scenarios in the case to make comparisons. Scenario A takes the FDRs into account, while the FDRs are not considered in Scenario B. The operating period of the two scenarios is set to be 100 hours.
Table 1. The state transition rates for a general FDR

| Transition rates (hour) | 0kW | 0.5kW | 1kW | 2kW |
|------------------------|-----|-------|-----|-----|
| 0kW                    | --  | 0.08  | 0.0133 | 0  |
| 0.5kW                  | 0.0294 | --   | 0.3235 | 0.0294 |
| 1kW                    | 0.0288 | 0   | --   | 0.3558 |
| 2kW                    | 0.0002 | 0.0001 | 0.0007 | -- |

Figure 2. The state-space diagram for a general FDR

Figure 3. System instant availability for different scenarios

Figure 4. System expected instant performance for different scenarios

Figure 5. System expected instant performance deficiency for different scenarios
The system time-varying reliability indices including IA, EIP, and EIPD are obtained utilizing the proposed techniques in Figure 3 –Figure 5. In these figures, the solid lines indicate the reliability indices for systems with FDRs, while the dotted line denote reliability indices for systems without the consideration of FDRs. These figures clearly demonstrate the reliability for power systems with FDR is higher than that of systems without FDRs. Moreover, the EENS for 100h of systems with FDRs and without FDRs are 60.29 MWh and 903.05 MWh, respectively. It indicate that in this case the system with FDRs is more reliable than the system without FDRs.

6. Conclusions
With the development of smart grid technologies, flexible demand resources have become active participants in demand response. The uncertainties from FDRs may influence the reliable operation of power system. Moreover, conventional reliability evaluations about generation systems, transmission systems and distribution systems have gained well developments. However, reliability model of FDRs in demand side gets little attention. A multi-state time-varying reliability model of FDRs utilizing $L_2$ transform is proposed in this paper. The proposed method can handle reliability evaluation for systems with time-vary probabilities and overcome the curse of dimensionality. The proposed technique is applied to the modified IEEE RTS to validate its feasibility and effectiveness.

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