Reliability evaluation of microgrid considering incentive-based demand response

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Abstract. Incentive-based demand response (IBDR) can guide customers to adjust their behaviour of electricity and curtail load actively. Meanwhile, distributed generation (DG) and energy storage system (ESS) can provide time for the implementation of IBDR. The paper focus on the reliability evaluation of microgrid considering IBDR. Firstly, the mechanism of IBDR and its impact on power supply reliability are analysed. Secondly, the IBDR dispatch model considering customer’s comprehensive assessment and the customer response model are developed. Thirdly, the reliability evaluation method considering IBDR based on Monte Carlo simulation is proposed. Finally, the validity of the above models and method is studied through numerical tests on modified RBTS Bus6 test system. Simulation results demonstrated that IBDR can improve the reliability of microgrid.

1. Introduction
Microgrid is a micro power distribution system that integrates DG, ESS, load, converter and protection device[1]. Microgrid can reduce the adverse effects of intermittent DG, improving power supply reliability and power quality. The reliability of microgrid is an important research content.

Demand response(DR) refers to the behavior that users adjust their power consumption actively according to the price signal or incentive mechanism[2]. According to the different response mechanisms, DR can be divided into time-based rates DR and IBDR[3]. IBDR refers to users get payments or preferential prices form reducing power usage during periods of system need or stress.

At present, the research on DR mainly focused on the mechanism analysis of DR[3], DR modeling for large-scale clean energy consumption[4], the benefit evaluation and support technology of DR[5] and so on. IBDR usually takes some time to respond and cannot reduce the load immediately to maintain a balance between power supply and demand in the event of a grid failure. Therefore, IBDR is usually not considered in the reliability assessment. In the microgrid, DG and ESS can provide response time for the implementation of IBDR to reduce load when microgrid switches to island mode. Loads of the microgrid are powered by DG and ESS before the load is curtailed.

In this paper, a reliability evaluation method of microgrid considering the IBDR is proposed. The basic idea is as follows: a) The dispatch model and response model on the IBDR are developed; b) Monte Carlo method is used to simulate the operating state of grid elements; c) Solve the dispatch model to get the amount of load curtailed by customers when microgrid is running on an island state; d) Solve the response model to get the actual amount of load reduced by each customer, and then determine the operating state of load points; e) Evaluate the reliability of microgrid.
2. Mechanism of IBDR
The IBDR programs studied in the paper includes interruptible load (IL) and emergency DR (EDR).

Customers in IL programs receive a rate discount or bill credit in exchange for agreeing to reduce load during system contingencies[3]. Customers can be penalized if they do not curtail. IL program has become an important tool for peak load shifting and handing of emergencies.

EDR program is implemented in a manner similar to that of IL program, where an incentive payment is set by the utility company and customer can obtain the compensation by reducing the load in the event of a reliability incident[6]. EDR is generally not used for peak load shifting. Customers can also choose to forgo the incentive payment and not curtail without penalty.

3. IBDR dispatch model

3.1. Comprehensive evaluation of customer in IBDR program
In this paper, the time to complete the response (M1), the response rate (M2) and the maximum load reduction (M3) are taken into account for the comprehensive evaluation of IBDR customer. M1 refers to the time from the moment that customer receives the response signal to the moment that load reduction is completed. M2 refers to the proportion of the number of times that customer actually curtailed the load in the total number of times that signal was received. M3 refers to the maximum amount of load that customer can curtail. The calculation method of M3 is shown as Equation (1).

\[ M_3 = P_{j,\text{max}} \lambda_{j,\text{max}} \]  

where \( P_{j,\text{max}} \) is the jth customer’s peak load; \( \lambda_{j,\text{max}} \) is the jth customer’s maximum load reduction ratio specified in the agreement.

The entropy method is used to determine the weight of the index, and the calculation steps are as follows: a) Standardize evaluation index; b) Calculate the entropy of the index; c) Calculate the entropy weight of the index. Then the jth customer’s comprehensive evaluation value is as following:

\[ W_j = \sum_{f=1}^{3} \omega_f b_{jf} \]  

where \( \omega_f \) is the entropy weight of the fth index; \( b_{jf} \) is the standardized result of the jth customer’s fth index, \( f=1,2,3 \), corresponding to \( M_1 \), \( M_2 \) and \( M_3 \) respectively.

3.2. Principle of customer load reduction
After the microgrid enters the island mode, the internal load of the microgrid is supplied by DG and ESS. At this time, the unbalanced power is mainly borne by ESS and the output stable DG, such as diesel engine and micro gas turbine. ESS cannot be a long time power supply due to limited capacity. Therefore, it’s necessary to allocate the output power of ESS to the customers in DR programs in advance. The allocation method is shown as Equation (3).

\[ \Delta P = P_{\text{ST}} - \sum_{d=1}^{D} P_{DG,d} - \sum_{d=1}^{D} P_{L,d} - P_{\text{loss}} \]  

where \( \Delta P \) is unbalanced power assigned to the customer; \( P_{\text{ST}} \) is the output power of ESS; \( D \) is the total number of nodes; \( P_{DG,d} \) is the DG output power of dth node; \( P_{L,d} \) is the load power of dth node; \( P_{\text{loss}} \) is loss of microgrid. As the ESS output power changes with time, \( \Delta P \) can be calculated by Equation (4).

\[ \Delta P = \overline{P_{\text{ST}}} \int_{t_1}^{t_2} P_{\text{ST}}(t) dt / (t_2 - t_1) \]  

where \( \overline{P_{\text{ST}}} \) is the average output of ESS; \( P_{\text{ST}}(t) \) is a function of ESS output over time; \( t_1 \) and \( t_2 \) are the starting and ending time for averaging ESS output.

3.3. IBDR dispatch model
The dispatch department assigns unbalanced power to customers during system contingencies. In order to improve the supply reliability and reduce the risk of customer’s default, the objective function
of dispatch model is to maximum the average evaluation value of customers that are dispatched. The dispatch model is shown as following:

$$\max W = \sum_{i=1}^{n} (W \Delta P_i) / \sum_{i=1}^{n} \Delta P_i$$

subject to:

$$\sum_{i=1}^{n} \Delta P_i = \omega \Delta P$$

$$\max(M_{1,i}) \leq T_s, \: i \in N$$

$$\forall i \in N, \frac{\Delta P_i}{P_i} \leq \lambda_{i,\text{max}}$$

where $n$ is the number of IBDR customers; $\bar{W}$ is the average evaluation value of customers; $\Delta P_i$ is load reduction of $i$th customer; $\omega_i$ is the margin of the load reduction and $\omega_i \geq 1$; $M_{1,i}$ is $i$th customer’s $M_1$; $N$ is the set of customers; $T_s$ is the remaining available time of ESS; $P_i$ is $i$th customer’s load before the response.

$T_s$ mainly depends on the capacity and output of ESS and is calculated by Equation (6).

$$T_s = \left( Q_{\text{re}} - Q_{\text{min}} \right) / \bar{P}_{ST}$$

where $Q_{\text{re}}$ is the remaining capacity of ESS; $Q_{\text{min}}$ is the minimum capacity limit for ESS.

The duration of customer’s response ($t_d$) can be calculated as following:

$$t_{d,i} = \omega_b T_d$$

where $\omega_b$ is response time margin coefficient and $\omega_b \geq 1$; $T_d$ is the expected repair time.

4. Customer response model

The response behavior of customer depends on whether customer can profit from the response. The paper develops a unified response model for customers in IL and EDR programs, which is based on the demand side goal optimization method and takes into account the uncertainty of DR. The customer response model is shown as following:

$$\max L = R - C_1 - C_2 - F$$

$$R = \begin{cases} \Delta P E_{\Delta t_d} & \Delta P \geq \Delta P_n \\ \Delta P E_{\Delta t_d} & \Delta P < \Delta P_n \end{cases}$$

$$C_1 = \int_{t_0}^{t_f} \alpha p(P(t) - \Delta P_d) dt$$

$$C_2 = \int_{r_0}^{t_f} \alpha p(P(t) - \Delta P_d) dt$$

$$F = \begin{cases} 0 & \Delta P_2 \geq \Delta P_n \\ (\Delta P_2 - \Delta P_n) p f & \Delta P_2 < \Delta P_n \end{cases}$$

subject to:

$$0 \leq \Delta P_d \leq P(t_0)$$

$$\alpha = \begin{cases} \alpha & \Delta P_2 \geq \Delta P_n \\ 1 & \Delta P_2 < \Delta P_n \end{cases}$$

$$t_s \leq t_{\text{re}}$$

where $L$ is total economic benefits; $R$ is the response gain; $C_1$ is the loss of power outage; $C_2$ is the electricity cost during the response period; $F$ is the unresponsive penalty; $\Delta P_n$ is the amount of load reduction required by the dispatch department; $\Delta P_d$ is the actual load reduction; $E$ is the compensation for the unit load reduction; $K_1$ and $K_2$ are constant coefficients; $u$ is a random value in the (0,1) interval; $t_0$ is the time to start the response; $\alpha$ is the discount rate; $p$ is the price; $P(t)$ is a function of the load over time; $p_f$ is penalty factor; $t_s$ is the time to complete the response; $t_{\text{re}}$ is the time to complete the response of the agreement.

5. Reliability evaluation method considering IBDR

Based on the Monte Carlo simulation, this paper presents a microgrid reliability evaluation method considering IBDR. The concrete steps are as follows:

1) Initialize the data, set the simulation years; 2) Generate the time to failure (TTF) for each grid component; 3) Select the component whose TTF is least as a faulty component, set its number to $m$, then the system’s normal working time $T_{TTF} = T_{TTFm}$; 4) Generate the time to repair (TRT) for
component \( m \); 5) Analyze the impact of component \( m \) failure on the load and divide the load into 5 categories. Class A: load not affected by the failure; Class B: load whose power supply can be restored after the fault has been isolated; Class C: load whose power supply can be restored through transfer the power; Class D: non-transferable load; Class E: microgrid load. 6) Class A load does not fail; The B, C and D class loads power outage time are fault isolation time, load transfer time and fault repair time; If microgrid does not enter the island mode, E class load does not fail; If not, proceed to the following steps:

a) Let \( L_1 \) be the set of loads that are cut and let \( L_2 \) be the set of loads that are not cut. Get the maximum output \( P_{max} \) and remaining capacity \( Q_{re} \) of ESS. b) Calculate the demand power \( P(t) \) of each load point and total power in the \( L_2 \) set, DG output power \( P_{DG}(t) \) and loss in \( t \) to \( t+\Delta t(\Delta t=15\text{min}) \) time period. c) If \( P_{DG}(t)>P_{t}(t)+P_{loss} \), go to step i. d) If \( P_{DG}(t)+P_{max}<P_{t}(t)+P_{loss} \), go to step j. e) If \( T_S<\Delta t \) \(+\max(t_{sn,i})\), go to step i. f) Calculate the maximum load reduction \( \Delta P_{max} = \sum_{i=1}^{n} P(t)\lambda_{i,max} \). If \( P_{DG}(t)>P_{t}(t)+P_{loss}\Delta P_{max} \), go to step h. g) If \( T_S<\Delta t \), go to step j. If not, go to step k. h) Solve the dispatch model and send the response signal to the customer. i) Solve the response model. If \( \sum\Delta P_{t,i} \geq \Delta P \), \( Q_{re}=Q_{re}\max(t_{sn,i}) \), \( t=t+\max(t_{sn,i}) \), and go to step l. If not, go to step g. j) Cut the load according to the importance and the position of the load and save the set \( L_1 \) and \( L_2 \). k) \( Q_{re}=Q_{re}\max(t_{sn,i}) \). l) If \( t \) is equal to the repair time, calculate the reliability index of the loads in the set \( L_1 \) and end this cycle. If not, \( t=t+\Delta t \) and go to step b.

7) If the simulation time does not reach the set time, go to step 2. 8) Calculate the reliability index of the load point and system.

6. Analysis of example

The modified RBTS Bus6 F4 feeder system is used for reliability evaluation and shown as figure 1.

![Figure 1. Modified RBTS Bus6 F4 feeder system](image)

WT is the wind turbine and its maximum output is 1MW. GT is the gas turbine and its rated output is 0.6MW. ST is the energy storage whose capacity is 1MW·h and output is 0.5MW. PCC is the common connection point between microgrid and distribution network. \( S_1 \), \( S_2 \) and \( S_3 \) are intelligent switches. The reliability parameters of the components are given in the reference[7]. The load data are given in the reference[8].

The following 3 cases are set up for reliability assessment and analysis. Case 1: no microgrid and no IBDR; Case 2: there is a microgrid but no IBDR; Case 3: there are microgrid and IBDR. Select \( LP \) 1, 9, 11, 20 and 22 as typical loads. Their annual failure rate and annual average interruption duration are shown in figure 2. The reliability indices of microgrid are shown in table 1.
In table 1, SAIFI is the system average interruption frequency index, SAIDI is the system average interruption duration index, ASAI is the average service availability index and EENS is the expected energy not supplied.

As can be seen from the simulation:
1) The implementation of IBDR can improve the reliability level of microgrid.
2) In contrast to Case 2 and Case 3, it can be seen that the implementation of IBDR can further improve the reliability of the microgrid under the same conditions of DG and ESS.
3) Compared with the reliability indices of the typical load points, it can be seen that the level of reliability improved by IBDR is related to the importance of the load. The more important the load is, the higher the degree of reliability improved by IBDR is.

7. Conclusions
Based on the characteristics of microgrid and IBDR, this paper applies the IBDR to the reliability evaluation of microgrid, proposes the dispatch model and response model of IBDR and evaluate the reliability of the modified RBTS Bus6 test system based on Monte Carlo simulation. The results show that the implementation of IBDR can improve the reliability of microgrid. However, IBDR is only one type of DR. In the next study, we need to study the optimal allocation and coordination control of DG, ESS and demand side resources to improve the reliability in combination with the time-based rates DR.

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