Reliability Evaluation of Distribution Systems Considering Demand Response

"Application of IEEE Std 1366™-2012"

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Abstract—**Recently, Demand Response (DR) is introduced into distribution systems as one of the pillars of the Smart Grid paradigm. DR changes real-time load demand, thus rendering traditional distribution system reliability evaluation methods obsolete. Two DR programs, time-of-use pricing and interruptible load are modeled in this project. Quantitative reliability indices defined in IEEE Std 1366™-2012 are adopted to evaluate reliability of distribution systems with a sequential Monte-Carlo simulation. The validity of above models and the influence of DR on distribution system reliability are studied through numerical tests on modified RBTS test system.**

Index Terms— **Demand response, distribution systems reliability, time-of-use pricing, interruptible load.**

I. INTRODUCTION

D ISTRIBUTION system reliability is defined as the ability of the distribution system to perform its function under stated conditions for a stated period of time without failure. It is vital as distribution system is directly associated with the satisfaction level of the customers. Recently, Demand Response is introduced into distribution system. It refers to the changes in the electricity usage by the end-use customers from their nominal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when the system reliability is jeopardized [1].

Ref. [2] studied the reliability benefit brought by DR for composite power systems. Ref. [3] focused on generation system reliability. Ref. [4] gave a general methodology for evaluating the impact of DR on distribution systems. However, how to correctly and effectively model certain programs of DR remains a problem. Also, little work has been done on the quantitative evaluation of the impact of DR on distribution system reliability.

This project proposes models for interruptible load and time-of-use pricing, which are two important programs in Demand Response. Then, reliability indices defined in IEEE Std 1366™-2012 [5] are utilized to give a quantitative assessment of the reliability benefit brought by DR. Numerical tests are conducted on RBTS test system [6] to validate above models and to study the influence of DR on reliability.

II. MODELING DR PROGRAMS

Demand Response programs include activities which aim to influence demand profile. These programs may have manifold forms. Three types of DR are distinguished: first dynamic pricing based on the use of time-varying prices, second voluntary load reduction and third the provision of ancillary services by load. In this section, two DR programs, time-of-use pricing and interruptible load, which belong to the first and second category respectively, are modeled.

A. Time-of-use Pricing

In a time-of-use program, the electricity prices are set for a specific time period. Prices paid for energy consumed during these periods are pre-established and known to consumers in advance, allowing them to vary their usage in response to such prices and manage their energy costs by shifting usage to a lower cost period or reducing their consumption overall [8].

In this project, three time-of-use periods are determined for a weekday. The morning and evening peak belong to on-peak time, late night belongs to off-peak time and the other time belongs to mid-peak time. Specific time division is shown in Table I. At weekends, late-night hours are still off-peak time and other hours belong to mid-peak time. Detailed regulated time-of-use prices are listed in Table II. A Chinese currency, Yuan, is used as the monetary unit in this research.

TABLE I
TIME-OF-USE PERIODS FOR WEEKDAYS

Time Slot	Corresponding Hours
On-Peak	9:00-11:00,16:00-21:00
Off-Peak	0:00-6:00
Mid-Peak	6:00-9:00,11:00-16:00,21:00-24:00

TABLE II
TIME-OF-USE PRICES

Time Slot	Prices/Yuan	
	Large Industrial Users	Others
On-Peak	0.7352	0.831
Mid-Peak	0.5758	0.6508
Off-Peak	0.2500	0.2826

The concept of electricity price elasticity is used to reflect demand reduction and demand shifting brought by time-of-use

programs. Electricity price elasticity can be divided into two types: self-elasticity and the cross-elasticity. In this model, only self-elasticity is considered and it is assumed to be constant. Table III gives the hourly self-elasticity within a day.

After time-of-use pricing, only the load profile is changed. Traditional distribution system reliability evaluation method is still applicable.

Hour	Self-elasticity (MWh/Yuan)
1	-0.05
2	-0.05
3	-0.06
4	-0.07
5	-0.06
6	-0.05
7	-0.07
8	-0.07
9	-0.09
10	-0.12
11	-0.14
12	-0.16
13	-0.16
14	-0.2
15	-0.18
16	-0.14
17	-0.16
18	-0.2
19	-0.25
20	-0.26
21	-0.16
22	-0.16
23	-0.13
24	-0.07

B. Interruptible Load

Interruptible load programs refers to DR activities that, in accordance with contractual arrangements, can interrupt consumer load at times of peak load by direct control of the utility system operator or by action of the consumer at the direct request of the system operator. It usually involves commercial and industrial consumers [9].

The introduction of interruptible load makes traditional distribution system reliability evaluation inapplicable. Power supply priority is introduced in the proposed interruptible load model in order to differentiate interruptible load from ordinary ones. Detailed traditional distribution system reliability evaluation procedure could be found in [10]. A fault analysis procedure is conducted after state sampling in every contingency of the reliability evaluation. When there is fault in the distribution system or deficiency of generation, load points

with high power supply priority will be sustained while load with low priority will be curtailed.

Detailed fault analysis procedure is shown in Fig.1. When every load point is connected to the main feeder, we assume that the power supply capability of the main feeder is sufficient enough that all load demand is supplied. However during faults, some load points are only connected to distributed generators. For every distributed generator with in the distribution system, there is a priority list of load points. Originally, power supply priority is determined by electrical distance between generators and load points. A distributed generator will preferentially supply a load point which has the lowest connection impedance with this generator. After the introduction of interruptible load programs, an interruptible load point will have the lowest power supply priority.
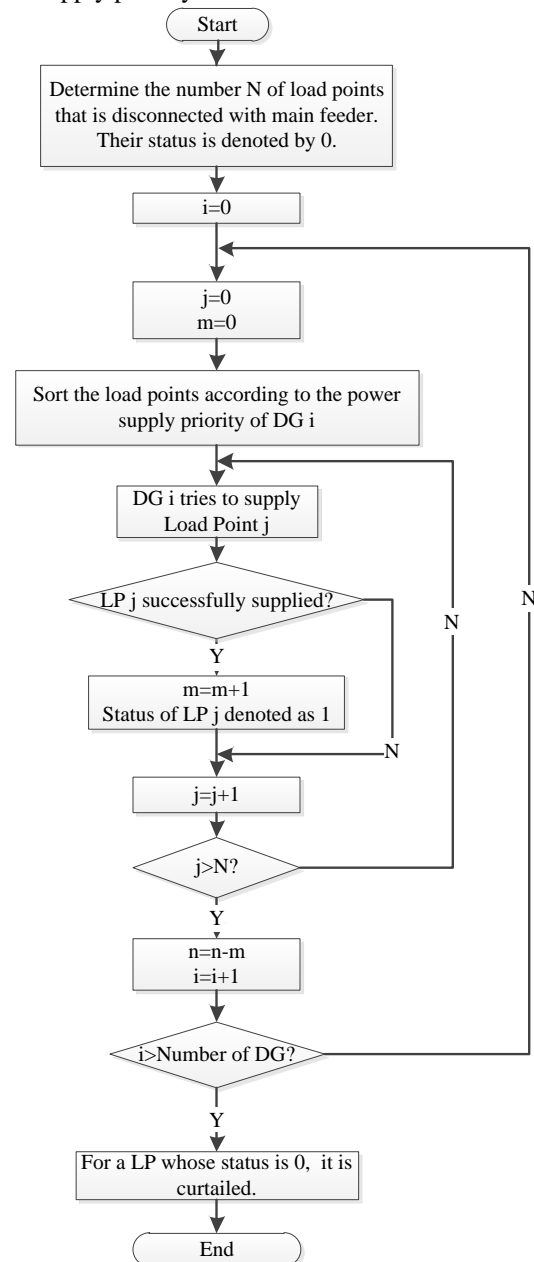

Fig.1 Flow chart for fault analysis in interruptible load model

III. APPLICATION OF IEEE STD 1366™-2012

IEEE Std 1366™-2012 identifies quantitative distribution reliability indices, which are used in this project to study the reliability impact of DR. Specifically, the following indices are used. Detailed explanations and definitions of these indices could be found in Ref. [5].

SAIFI: System Average Interruption Frequency Index
SAIDI: System Average Interruption Duration Index
CAIDI: Customer Average Interruption Duration Index
ASAI: Average Service Availability Index

Besides, a well-acknowledged index, EENS, is used to represent the energy not served in a distribution system.

IV. SYSTEM STUDIES

Extensive case studies are conducted on the modified RBTS Bus6 F4 test system. A sequential Monte-Carlo simulation is conducted on the test system to obtain the reliability indices. The influence of the two DR programs on system reliability has been analyzed in detail.
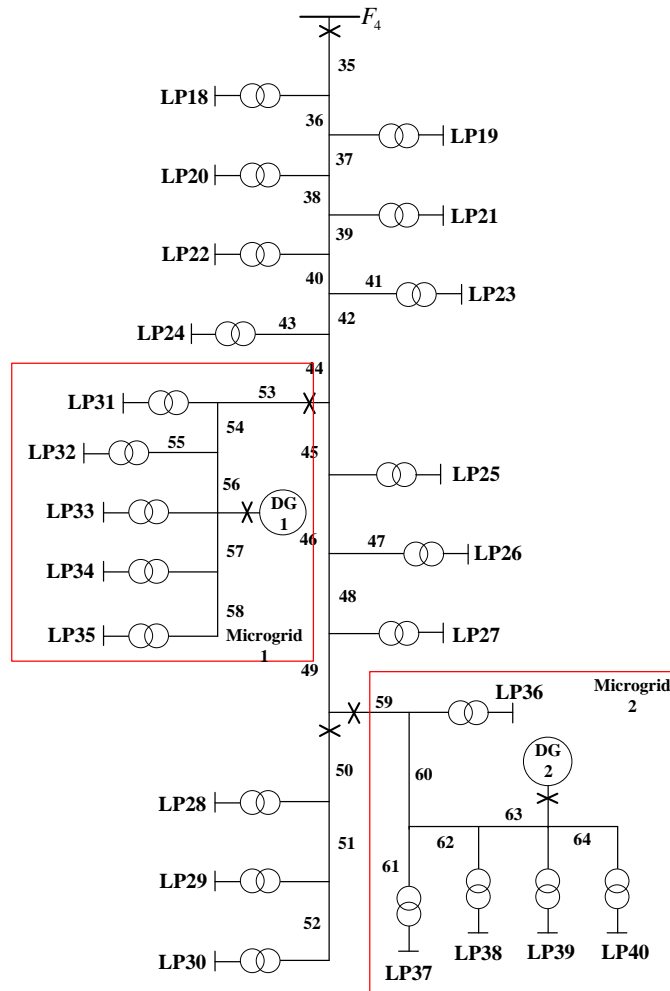
A. The modified RBTS BUS6 F4 Feeder

Fig.2 Modified RBTS Bus6 F4 system

As in Fig.2, two microgrids are integrated into this feeder, each containing a distributed generator, rated at 15MW. Detailed test system information can be found in [6]. It is notable that only average and peak load data are given in [6]. The sequential load curve without demand response is obtained based on the method proposed in [7], which is shown in the solid line in Fig.3.

B. Reliability Impact Brought by Time-of-use Pricing

After the introduction of time-of-use (TOU) pricing, load profile will be changed according to user elasticity. Based on the model in Section II.A, load curve after the introduction TOU program is shown in the dashed line of Fig.3. It highlights that during on-peak periods, electricity consumption is reduced. At the same time, off-peak load demand is increased. Due to the fact that only self-elasticity is considered in this project, the daily power consumption is reduced, rather than unchanged.
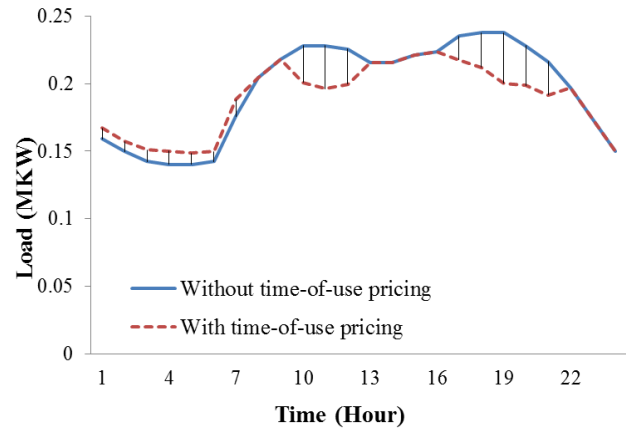

Fig.3 Change of the load curve after time-of-use pricing

Reliability evaluation results are shown in the table below.

TABLE III
RELIABILITY INDICES CONSIDERING THE TOU PROGRAM

Index	Without TOU	With TOU	Improvement (%)
SAIFI*(int/yr)*	0.953367	0.953595	-0.024
SAIDI*(hr/yr)*	7.41884	7.40806	0.145
CAIDI*(hr/yr)*	7.78172	7.76856	0.169
ASAI	0.999151	0.999152	0.00012
EENS*(MWh/yr)*	72.81647	70.65625	2.967
Annual Power Consumption *(MWh)*	58658.46	57071.97	2.705

It could be seen from Table III that except for the detriment of SAIFI, all other indices are improved. However, the improvement rate is low. Due to the fact that only self-elasticity is considered in this project, annual power consumption is also reduced, which leads to considerable improvement of EENS.

C. Reliability Impact Brought by Interruptible Load

The introduction of interruptible load would lead to load curtailment. Compared to traditional interruption in reliability evaluation, DR often curtails loads with advance notice. Also, consumers get benefits from curtailed load. However, it is disputed whether interruption brought by DR should be considered as load curtailment in the traditional sense.

Therefore, the reliability evaluation of modified RBTS is conducted in the following three scenarios:

Scenario 1: Without interruptible load
Scenario 2: With interruptible load. Load curtailment brought by DR is not considered as interruption.
Scenario 3: With interruptible load. Load curtailment brought by DR is considered as traditional interruption.

According to proximity, the original load supply priority within microgrids is list as below:

Microgrid 1: LP33>LP34>LP32>LP35>LP31
Microgrid 2: LP39>LP40>LP38>LP37>LP36

When DR program (in Scenario 2 and 3) is introduced, load point 34 and 37 are assumed to be interruptible load. Then, the load supply priority within microgrids is list as below:

Microgrid 1: LP33>LP32>LP35>LP31>LP34
Microgrid 2: LP39>LP40>LP38>LP36>LP37

Reliability evaluation results are shown in Table IV.

TABLE IV
RELIABILITY INDICES OF THE THREE SCENARIOS

Index	Scenario 1	Scenario 2	Scenario 3
SAIFI(int/yr)	0.953367	0.969449	0.971253
SAIDI(hr/yr)	7.41884	7.35176	7.35737
CAIDI(hr/yr)	7.78172	7.58345	7.57513
ASAI	0.999151	0.999159	0.999158
EENS(MWh/yr)	72.816	68.896	72.884

By comparing indices in Scenario 1 with indices in Scenario 2 and 3, it could be seen that after the introduction of interruptible load, SAIDI and CAIDI are reduced. ASAI almost remain unchanged. SAIFI is increased. If load curtailment brought by DR is not considered as interruption, EENS is considerably reduced. Otherwise, as indicated in Scenario 3, EENS is not improved.

From the indices we could assume that the reliability of this distribution system is not considerably improved, especially when load curtailment brought by DR is considered as traditional interruption. However, it should be pointed out that by determining interruptible loads, DR normally targets less sensitive loads. Those sensitive loads with high power supply priority are able to stay energized. By giving advance notice that allows customers to shift their demand and targeting less sensitive loads, interruptible load programs improve power supply efficiency.

D. Comprehensive Analysis

In Section IV.B and Section IV.C, the two DR programs are studied individually. Sometimes these two programs are conducted in a distribution system simultaneously. Comprehensive analysis results are described below.

TABLE IV
COMPREHENSIVE STUDY OF THE TWO DR PROGRAMS

Index	Without DR	TOU	Interruptible Load	Interruptible Load & TOU
SAIFI (int/yr)	0.953367	0.953595	0.969449	0.969353
SAIDI (hr/yr)	7.41884	7.40806	7.35176	7.34465
CAIDI (hr/yr)	7.78172	7.76856	7.58345	7.57686
ASAI	0.999151	0.999152	0.999159	0.999159
EENS (MWh/yr)	72.81647	70.65625	68.896	66.70548

Table IV shows that the individual characteristics of the two DR programs are also revealed in the comprehensive study. Despite the increase of SAIFI brought by the interruptible load program, all other four indices are most optimistic when the two programs are conducted at the same time.

V. CONCLUSIONS

Two Demand Response programs, time-of-use pricing and interruptible load, are modeled in this project. Reliability indices defined in IEEE Std 1366™-2012 are utilized to give a quantitative assessment of the reliability benefit brought by the two DR programs.

System studies conducted on modified RBTS lead to following conclusions. Time-of-use pricing changes the demand profile, which results in a smoother load curve and better reliability performance. Especially EENS is considerably improved due to the reduction of daily load demand. Interruptible load programs alter power supply priority. A fault analysis procedure is proposed. Less sensitive loads are curtailed with advance notice at times of faults or high wholesale market prices, which leads to moderate improvement of reliability indices.

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