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Evaluation of Power System Reliability Considering Direct Load Control Effects

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Article Info	ABSTRACT
	With the development of deregulated power systems and increase of prices in some hours of day, demand side management programs were noticed more by customers. In restructured power systems, DSM programs are introduced as DEMAND RESPONSE. In this paper we try to evaluate the effect of DR programs on power system reliability and nodal reliability. In order to reach to this target, Direct Load Control program, as the most common demand response program, is considered. Effects of demand response programs on system and nodal reliability of a deregulated power system are investigated using direct load control and economic load model, DC power-flow-based optimal load curtailment objective and reliability evaluation techniques. The proposed method is evaluated by numerical studies based on a small reliability test system (RBTS), and simulation results show that demand response program can improve the system and nodal reliability.

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1. INTRODUCTION

Demand Side Management (DSM) introduced by Electric Power Research Institute (EPRI) in the 1980s. DSM consists of a series of activities that governments or utilities design to change the amount or time of electric energy consumption, to achieve better social welfare or some times for maximizing the benefits of utilities or consumers. In fact, DSM is a global term that covers activities such as: Load Management, Energy Efficiency, Energy Saving and so on [1]. Electric power industry bas been faced with restructuring and deregulation. Meanwhile a few new terms created in this new environment, such as "Demand Response" (DR).

DR can be defined as the changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time. Further, DR can be also defined as the incentive paymentsdesigned to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized [2].

Demand response consists of a series of activities that governments or utilities design to change the amount or time of electric energy consumption, to achieve better social welfare or some times for maximizing the benefits of utilities or consumers.

The benefits of DR include increased static and dynamic efficiency, better capacity utilization, pricing patterns that better reflect actual costs, reduction of price spikes, decentralized mitigation of market power, and improved risk management.

A recent study estimated the prospective benefits of active demand response at $7.5 billion by 2010 (ICF 2002). Other studies, described in GAO (2004), give further details of the benefits that have already been generated because of demand response and active retail choice.

Federal Energy Regulatory Commission (FERC) reported the results of DR investigations and implementations in US utilities and Power Markers [3], [4]. In the mentioned report, DR is divided into two basic categories and several subgroups:

A- Incentive-based programs:

A-1- Direct Load Control (DLC)

A-2- Interruptible/curtail able service (I/C)

A-3- Demand Bidding/Buy Back

A-4- Emergency Demand Response Program (EDRP)

A-5- Capacity Market Program (CAP)

A-6- Ancillary Service Markets (A/S)

B- Time-based programs:

B-1- Time-of-Use (TOU) program

B-2- Real Time Pricing (RTP) program

B-3- Critical Peak Pricing (CCP) Program

The most usual demand response program is Direct Load Control (DLC), in which utilities have the ability to remotely shut down participant's load on a short notice.

DR is able to change the amount and time of electric energy usage so that the best efficiency of consumption takes place in the peak interval [5].

There is a growing concern about the reliability of power systems under a market environment, especially after the blackouts in North America and Europe in 2003.

Bulk power system operators primarily rely on adjustments in generation output (MW movements up or down) to keep the system reliability.

In principle, changes in electricity demand could serve as well as generator movements in meeting the reliability requirements [6]. So, customer loads could be able to participate in these markets. The participation of these resources will either enhance reliability or lower costs of maintaining reliability for all customers and will save money for participating customers.

This paper investigates the impacts of DR programs on system and nodal reliability in state enumeration approach. A small reliability test system, RBTS, is studied, and simulation results show that demand response can improve the system and nodal reliability.

This paper is organized in five sections. Section 2 defines the load economic model which is used to evaluate the participation in DLC program and explains the economic analysis formulation. Reliability Index Calculation is discussed in section 3. Section 4 presents the numerical results which are tested on RBTS and finally section 5 is dedicated to conclusions.

2. MODELING OF DEMAND RESPONSEM

In the beginning of the deregulation, usually consumers had not effective participation in the power markets and therefore they were not able to response to the prices effectively. However, the development of the restructured power systems has been accompanied by many problems, for example reduced system reliability. Figure 2 shows how the demand elasticity could effect on electricity prices [7].
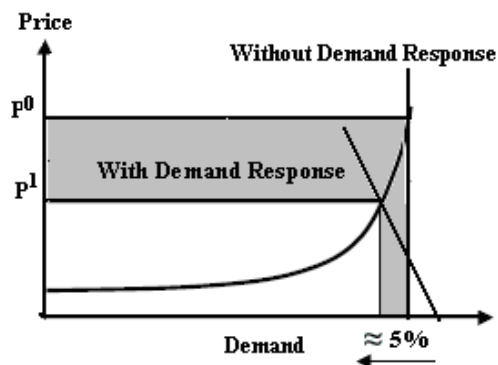

Figure1. Effect of demand variation on the electric energy price [4]

Elasticity is defined as the ratio of the relative change indemand to the relative change in price [5]:

$$E = \frac{\partial q}{\partial \rho} = \frac{\rho_0}{q_0} \cdot \frac{dq}{dp} \tag{1}$$

Where:

$\Delta d(t_i)$: Demand changes in time interval t_i

$\Delta \rho(t_i)$: Price changes in interval t_i

$\Delta \rho(t_j)$: Price changes in time interval t_j

According to Equation (2), self elasticity (ξ_{ii}) and cross elasticity (ξ_{ij}) can be written as [8]:

$$\xi_{ii} = \frac{\Delta d(t_i)/d_0}{\Delta \rho(t_i)/\rho_0}$$

$$\xi_{ij} = \frac{\Delta d(t_i)/d_0}{\Delta \rho(t_j)/\rho_0} \tag{2}$$

Where:

$\Delta d(t_i)$: Demand changes in time interval t_i

$\Delta \rho(t_i)$: Price changes in interval t_i

$\Delta \rho(t_j)$: Price changes in time interval t_j

Self elasticity and cross elasticity are negative and positive values, respectively. If the relative change in demand is larger than the relative change in price, the demand is said to be elastic, on the other hand, if the relative change in demand is smaller than the relative change in price, the demand is said to be inelastic. So the elasticity coefficients can be arranged in a 24 by 24 matrix E.

The detailed process of modeling and formulating how the DR program affects on the electricity demand and how the maximum benefit of customers is achieved, are discussed in [9]. Accordingly the final responsive economic model is presented by (3):

$$d(i) = \left\{ d_0(i) + \sum_{j=1}^{24} E_0(i,j) \cdot \frac{d_0(i)}{\rho_0(j)} \times A(j) + \frac{E(i)[\rho(i) - \rho_0(i) + A(i)]}{\rho_0(i)} \right\} \quad i = 1, 2, \ldots, 24. \tag{3}$$

The above equation shows how much should be the customer's demand in order to achieve maximum benefit in a 24-hours interval.

Time period is assumed to be one hour. Variable load curve for 24 hours within one day are considered in the simulations.

So the elasticity coefficients can be arranged in a 24 by 24 matrix E [7].

$$E = \begin{bmatrix} \xi_{1,1} & \xi_{1,2} & \cdots & \xi_{1,23} & \xi_{1,24} \\ \xi_{2,1} & \xi_{2,2} & \cdots & \xi_{2,23} & \xi_{2,24} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \xi_{23,1} & \xi_{23,2} & \cdots & \xi_{23,23} & \xi_{23,24} \\ \xi_{24,1} & \xi_{24,2} & \cdots & \xi_{24,23} & \xi_{24,24} \end{bmatrix} \tag{4}$$

3. REALIBILITY INDEX CALCULATION

Reliability evaluation methodologies of power systems are systematically described in reference [8]. According to the method of selecting system state, there are two basic methods: state enumeration and Monte

Carlo sampling. The composite system reliability assessment is a complex calculation project, which generally includes the following procedures [10]:

a) Determination of component failures and load curve models;
b) Selection of system states;
c) Identification and analysis of system problems;
d) Calculation of reliability indices.

Both the state enumeration and Monte Carlo simulation method can be applied to composite system reliability evaluation. These two methods use different approaches to select system states and have different forms of formulas to calculate reliability indices. The techniques of identifying and analyzing problems in a system state are the same. These include power flow and contingency analysis for problem recognition and optimal power flow for remedial actions. In our following simulation, the enumeration simulation method is adopted to select system states.

The formulation of load curtailment determination under contingency s using DC load flow and customer interruption load can be depicted by the optimization of Equation (5).

$$
\begin{cases}
\min \ \sum_{i \in ND} LC_i^s \\
\sum_{i \in NG} PG_i - PD_i + LC_i^s = \sum_j B_{ij}(\delta_i - \delta_j) \\
-P_{ij}^{\max} \leq B_{ij}(\delta_i - \delta_j) \leq P_{ij}^{\max} \\
0 \leq LC_i^s \leq PD_i \\
PG_i^{\min} \leq PG_i \leq PG_i^{\max}
\end{cases}
\tag{5}
$$

LC_i^s is the load curtailment bus i under contingency s, PGi and PDi are generation output and load power bus i, NG, ND are the sets of generation buses, load buses in the system. $PG_i^{\min}$ is the minimum output of real power of generator i; $PG_i^{\max}$ is the maximum output of real power of generator i. $P_{ij}^{\max}$ is the maximum real power flow allowed through line ij. Bij is the susceptance between nodes i and j.

This optimal model of load curtailment is a linear programming problem that is easily solved by conventional linear programming methods.

Indices of system reliability are:

LOLE: Loss of load expected is Index load Average Interruption Duration, in [h], is the mean duration per interruption.

ENS: Energy Not Supplied, in [MWh/day], is the total amount of energy which is expected not to be delivered to the loads.

AENS: Average Energy Not Supplied, in [MWh/C/day], is the average amount of energy not supplied, for all customers.

Additional calculated indices for the load points are:

AID: Average Interruption Duration [h].

LPENS: Load Point Energy Not Supplied [MWh/day].

4. NUMERICAL RESULT

A case study based on the IEEE 6-bus system is presented in this section, In order to show the effect of demand response program on system reliability of a deregulated power system [11]. The RBTS has 11 generating units of various sizes, with the total installed capacity of 240 MW and a total system peak demand of 185MW spreading out among 5 of the 6 system buses. The single line diagram of RBTS is shown in Figure 2.

The amount of incentive and the price of electrical energy in DLC program formulation are assumed to be same and equal to 50 $/MWh. The elasticity of the load is shown in Table. 1.

A typical load curve of a real world network is selected to test and analyze the effect of DLC program, Figure 3 [12]. The load curve is divided into three intervals: Low load period (12.00 p.m. to 9:00 a.m.), off-peak period (10:00 a.m. to 19:00 p.m.) and peak period (19:00 p.m. to 12:00 p.m.).
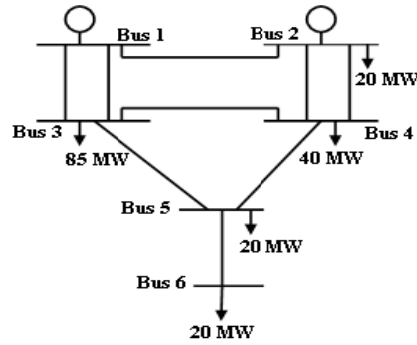
Figure 2. Single line diagram of the RBTS

Table 1. Self and crosselasticities

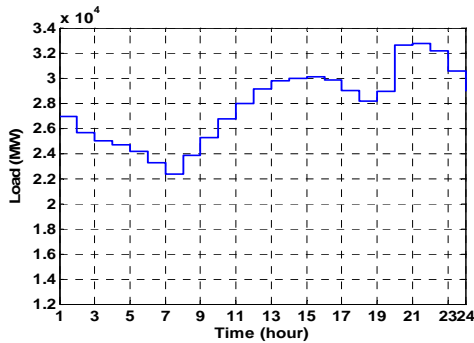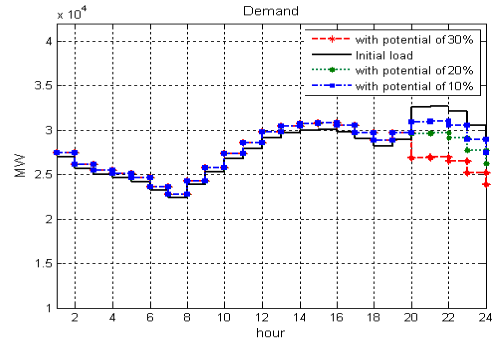|	Peak	Off-Peak	Low
Peak	-0.02	0.0032	0.0024
Off-Peak	0.0032	-0.02	0.002
Low	0.0024	0.002	-0.02

Figure 3. Load of test system

Figure 4. Effect of different scenarios of DLC on demand

Three scenarios are assumed for the different participant's potential in DLC program. It means that the potential of the customers that take part in DLC program assumed to be 10%, 20%, and 30% of all customers. The load curve before and after implementation of DLC program for different scenarios are represented in Figure 4.

As it can be seen, by implementation of DLC program, based on the difference between elasticities in different periods, loads are transferred from peak periods to valley periods. Without demand response programs, the system peak load is 185 MW; considering demand response programs, however, the system peak load is 180.87MW. Load duration curve with and without DR program shows in Figure 5.
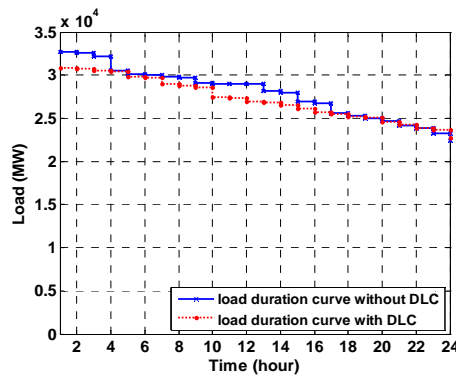

Fig. 5.Load duration curve with and without DR programs

In order to show the effect of demand response on the load curve and system and nodal reliability of a deregulated power system, a test system, RBTS [11], has been simulated using the reliability evaluation techniques. Above program maximize the profit of customers moreover influencing the system and nodal reliability.

Two scenarios will be observed in this paper: 1-Test of system without considering DR programs, 2-Test of system with considering DR programs.

By Simulation and test system, these results will be driven for the reliability of total system (Table 2).

Table 2. System reliability Idices of The RBTS

	Without Considering DR	Considering DR
LOLE	0.027947	0.027863
ENS	116.673	109.626
AENS	23.3346	21.925

For system nodes these results are driven (Table 3, 4):

Table 3. Average Interruption Duration [Hour]

	Without Considering DR	Considering DR
Load 6	0.02586	0.02583
Load 3	0.02578	0.02575
Load 4	0.02574	0.02571
Load 5	0.02580	0.02577

Table 4 Load Point Energy Not Supplied (MWh/day)

	Without Considering DR	Considering DR
Load 6	54.7965	51.4890
Load 3	13.8049	12.9813
Load 4	12.3539	11.6074
Load 5	25.6929	24.1419

The results show that direct load control programs improves the reliability of the system and from the comparison of nodal reliability indices with andwithout considering demand response programs especially DLC program, it is shown that thenodal reliability is also improved considering demand response programs.

5.   CONCLUSION

This paper evaluate the effects of demand response programs especially direct load control on system and nodal reliability of a deregulated power system using direct load control and economic load model, DC power-flow-based optimal load curtailment objective and reliability evaluation techniques. From the simulation results it can be seen that demand response programs improves the system reliability and nodal reliability of a deregulated power system.

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