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Demand Response Impact on Market Operator's Revenue and Load Profile of a Grid Connected with Wind Power Plants

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Abstract – Economic properties of an integrated wind power plant (WPP) and the demand response (DR) programs in the sample electricity market are studied. Time of use (TOU) and direct load control (DLC) are two of the DR programs that are applied in the system. The influences of these methods and the incentive payments by market operator's (MOs) with variable elasticity are studied. It is observed that DR with TOU and DLC programs together yields better revenue and energy saving for MOs.

Keywords: Wind power plant (WPP), Demand response (DR), Time of use (TOU), Direct load control (DLC), Market operator's (MOs)

1. Introduction

Creation and use of renewable energy resources have become important due to global warming and environmental issues associated with usage of fossil fuels. Among the renewable energy resources wind power generation is preferred choice in terms of usage and importance. The increased use of wind power raises concerns about energy security, fuel price instability, and the environmental challenges, resources and diversification of energy resources. Unlike other types of renewable energy resources, wind technology is the result of the development of wind generators over traditional units with comparable cost and capacity ratings [1, 2].

The general definition of market operator's(MOs) consider for this paper is a centralized institution being responsible for operation of an organized market for the (commercial) exchange of energy on behalf of market participants [3]. One of the major objectives of MOs consisting of large number of wind power plants is to increase their revenue. This goal can be achieved with the pay incentives for wind farms and other policies including demand response (DR). Technologies that exploit DR and demand side management (DSM) are one of the choices that must be considered in system planning, due to the commercial probability of regulating consumption in response to the variation in wind power generation [4].

In this study, we discuss how the DR programs with regard to consumption can efficiently raise revenue of the system and perform operations scheduling of power systems are investigated. Time of use (TOU) and direct load control (DLC) are two DR programs that are considered in this study.

The rest of this paper is organized in the following order. Section 2 describes the wind power generation. Section 3 categorizes demand response programs. Section 4 presents the relation between wind power and DR and provides a mathematical formulation of the proposed framework. Section 5 presents implementation of the proposed method in three scenarios and numerical study, in this part discuss about the results. Finally, the last section is devoted to conclusion.

2. Wind Power Generation

The use of wind power increases from year to year because of low operating cost and advanced technology. Despite these advantages, the use of wind power has several drawbacks; the most critical drawback is the uncertainty. This problem is more serious in power market. Hence, some amount of reserve is necessary to support wind generation. To solve these problems and improve the flexibility of the network, several technical and financial schemes proposed in recent years are as follows [2, 5, 6].

Technical methods of use of storage such as batteries, pumped storage, connecting to the adjacent network, combined heat and power (CHP), using thermal storage for reserve and DSM techniques [6].

The power curve for sample wind turbine is illustrated in Fig. 1, Wind speed (V_W) lower than Cut-in wind speed (V_C) and higher than Cut-out wind speed (V_{Co}) produces

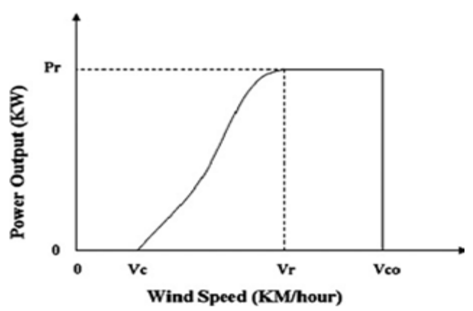

Fig. 1. Wind turbine power curve

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zero power output, also the wind speed, which is between the rated speed (V_r) and the cut-out speed (V_{Co}) produces the rated power.

3. Demand Response

The U.S. Department of Energy (DOE) defines DR as: "Changes in electric usage by demand-side resources from their normal 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 system reliability is jeopardized". DR in this explanation can be classified into two clusters: time-based rates (TBR) and incentive-based program (IBP) demand response. Several sub groups are illustrated in the following chart [7].

Fig. 2. Demand response chart

This paper focuses on time of use (TOU) and Direct Load Control (DLC) programs. In TOU programs, the electricity prices are resolutely based on the production costs in the same period [7]. Thus, usually the price in the peak period will be high, in the off-peak period will be moderate, and in the low load period will be cheap. DLC programs denote programs in which a utility or system operator remotely shuts down or local reliability contingencies in exchange for an incentive payment or cycles a customer's electrical equipment on short notice to address system or bill credit.

4. Wind Power and Demand Response

In 2001 ordinance the European Commission (EC) set the goal of 22% gross electrical energy generation from renewable energy for the European countries by 2010. To satisfy this goal, the installation of extra renewable generation capacity is strategic planning, which the major share of the growth is in wind power, whose goal is to achieve 5700 MW by 2012, and 8000 MW by 2020. In this scenario the major share penetration of renewable generation is from a wind power plant (WPP) and other alternating resources. It means that the electrical system needs to be prepared to coordinate the effects of the unpredictability and uncertainty of the wind power generation availability. This worry was usually directed to the upgrade of wind researches and discovery of answers created on adjustable hydropower dams [8], and other choices interconnected to the energy storage technologies and energy supply (e.g. back-up generation). Technologies used by DSM and DR are choices that must be considered by the system planner due to the inexpensive possibility to revise the consumption in response to the variety in the wind energy generation.

4.1 MOs Revenue and responsive load mathematical model

In order to assess the impact of the contribution of consumers in the DR program on the attributes of the load profile, the expansion of flexible load commercial models are needed. Schweppe and his colleagues have developed and formalized models of the spot price of electricity in 1989. They provided a system where consumers They envisaged a system where consumers could regulate their demand up or down contingent on spot prices [9]. As this model can perhaps be taken into consideration when organizing generation and setting the price of electricity in a pool based on electricity market is explained by Kirschen [10]. Electricity prices will directly impact the demand and consumption sets with electricity prices. The elasticity of demand sensitivity over price change is [11]:

$$e = \frac{\rho_0}{q_0} \bullet \frac{\partial q}{\partial \rho} \quad (1)$$

Where (e) The elasticity of demand, q energy demand Mwh , ρ energy prices $\$/Mwh$, q_0 initial demand, ρ_0 initial price, By definition, the elasticity of demand for the i^{th} interval to interval j is defined as:

$$e(i,j) = \frac{\rho_0(j)}{q_0(i)} \bullet \frac{\partial q(i)}{\partial \rho(j)} \quad (2)$$

It shows how consumer price changes in the i^{th} interval due to change consumption in the interval j . In a period when price increases, Consumers tend to use energy is reduced or willing to transfer loads to another time interval if possible. Always, Cross-elasticity ($i \neq j$) is positive, and own elasticity ($i = j$) is negative. If price of electricity vary during different periods, the demand response can be one of the following:

Some consumption could be moved from the peak period to the off-peak or low periods (e.g. industrial loads). Such behavior is named multi period sensitivity and it is evaluated by "cross-elasticity" which is positive. Several loads are not able to move from one period to another (e.g. lighting loads) and they could be only on or off. So, such loads have sensitivity just in a single period and it is called "self-elasticity", and it has a negative value [12, 13].

In this paper, effects of TOU and DLC programs execution on the revenue and single period load profile are studied. In DLC programsame as EDRP program incentive for customers which denotes the changes of the consumer's demand with regards to change of the electricity price is considered. The load consumption considering TOU, DLC and value of incentive paid by market operator's is given by the following equations [14, 15]:

Suppose that:

$L(t)$ = Customer demand in t^{th} hour (MWh).
$L_0(t)$ = Initial Customer demand in t^{th} hour (MWh).
$\rho(t)$ = Spot electricity price in t^{th} hour (\$/MWh).
$\rho_0(t)$ = Initial Spot electricity price in t^{th} hour(\$/MWh)
$A(t)$ = Incentive in t^{th} hour (\$/MWh).
$B(d(t))$ = Customer's income in t^{th} hour (\$).
e = self-elasticity

And also suppose that the customer changes its demand from $L_0(t)$ (initial value) to $L(t)$, based on the value of price to initial price.

$$\Delta L(t) = L(t) - L_\circ(t) \text{ (Mwh)} \tag{3}$$

Therefore, the customer's benefit, S(\$), for t^{th} hour will be as follow:

$$S(L(t)) = B(L(t)) - (L(t) \cdot \rho(t)) \text{ (\$)} \tag{4}$$

To maximize the customer's benefit, $\frac{\partial S}{\partial L(t)}$ should be equal to zero:

$$\frac{\partial S}{\partial L(t)} = \frac{\partial B(L(t))}{\partial L(t)} - \rho(t) = 0 \tag{5}$$

$$\frac{\partial B(L(t))}{\partial L(t)} = \rho(t) \tag{6}$$

The most benefit-function used, is the quadratic benefit function [9]:

$$B(L(t)) = B_0(t) + \rho_0(t)\left[L(t) - L_0(t)\right] \bullet \left\{1 + \frac{L(t) - L_0(t)}{2 \bullet e(i,i) \bullet L_0(t)}\right\} \tag{7}$$

where:

$B_0(t)$ = Benefit when the demand is at nominal value $L_0(t)$
$\rho_0(t)$ = Nominal electricity price when the demand isnominal. Considering (6) and (7):

$$\rho(t) = \rho_0(t) \bullet \left\{1 + \frac{L(t) - L_0(t)}{e(i,i) \bullet L_0(t)}\right\} \tag{8}$$

Therefore, customer's consumption considering TOU program will be as follow:

$$L(t) = L_0(t) \bullet \left\{1 + \frac{e(i,i) \bullet \left[\rho(t) - \rho_0(t)\right]}{\rho_0(t)}\right\} \tag{9}$$

In the above equation, if $L(t)$ be equal to $L_0(t)$, the electricity price will not change and price elasticity will be equal to zero.

So, incentive prize, P (\$), due to running DLC will be as:

$$P(\Delta L(t)) = A(t) \bullet \Delta L(t) \text{ (\$)} \tag{10}$$

Therefore, the customer's benefit, S(\$), for t^{th} hour will be as follow:

$$S(L(t)) = B(L(t)) - L(t) \ \rho(t) + P(\Delta L(t)) \tag{11}$$

To maximize the customer's benefit, $\frac{\partial S}{\partial L(t)}$ should be equal to zero:

$$\frac{\partial S}{\partial L(t)} = \frac{\partial B(L(t))}{\partial L(t)} - \rho(t) + \frac{\partial P(\Delta L(t))}{\partial L(t)} = 0 \tag{12}$$

$$\frac{\partial B(L(t))}{\partial L(t)} = \rho(t) + A(t) \tag{13}$$

The most benefit-function used, is the quadratic benefit function [9]:

$$B(L(t)) = B_0(t) + \rho_0(t) \bullet \left[L(t) - L_0(t)\right] \left\{1 + \frac{L(t) - L_0(t)}{2 \bullet e(i,i) \bullet L_0(t)}\right\} \tag{14}$$

where:

$B_0(t)$ = Benefit when the demand is at nominal value $L_0(t)$
$\rho_0(t)$ = Nominal electricity price when the demand is nominal.

Considering (13) and (14):

$$\rho(t) + A(t) = \rho_0(t) \bullet \left\{1 + \frac{L(t) - L_0(t)}{e(i,i) \bullet L_0(t)}\right\} \tag{15}$$

$$\rho(t) - \rho_0(t) + A(t) = \rho_0(t) \bullet \left\{\frac{L(t) - L_0(t)}{e(i,i) \bullet L_0(t)}\right\} \tag{16}$$

Therefore, customer's consumption considering DLC program will be as follow:

$$L(t) = L_0(t) \bullet \left\{ 1 + \frac{e(i,i) \bullet \left[\rho(t) - \rho_0(t) + A(t) \right]}{\rho_0(t)} \right\} \quad (17)$$

In the above equation, if $A(t)$ be equal to zero $L(t)$ will be equal to $L_0(t)$. Thus, the electricity price will not change and price elasticity will be equal to zero.

From the above equations, we can obtain MOs revenue $R(t)$ in 24 hours considering DR as given below:

$$R(t) = R_{WPP}(t) \pm R_{trade}(t) - C_{incentive}(t) \quad (18)$$

$R_{WPP}(t)$ Represent WPP revenue from energy sales in electricity market and this WPP consist of n wind turbine, $R_{trade}(t)$ represent revenue from energy trade with adjacent grid. This is positive if MOs sell energy to adjacent grid and is negative if MOs buy energy from adjacent grid. $C_{incentive}(t)$ Represent cost of incentive payment.

$$R_{WPP}(t) = \sum_{t=1}^{24} \sum_{n=1}^{N_g} P_{WPP}(t,n) \bullet \rho(t) \quad (19)$$

$$R_{trade}(t) = \sum_{t=1}^{24} P_{trade}(t) \bullet \rho(t) \quad (20)$$

$$C_{incentive}(t) = \sum_{t=1}^{24} P_{DR}(t) \bullet A(t) \quad (21)$$

Constraints are given by Eq. (22) to Eq. (26).

$$P_{WPP}(t) + P_{DR}(t) + P_{trade}(t) = P_L(t) \quad (22)$$

$$P_{DR}(t) = P_L(t) - L(t) \quad (23)$$

$$P_{WPP,Min} \le P_{WPP}(t) \le P_{WPP,Max} \quad (24)$$

$$P_{trade,Min} \le P_{trade}(t) \le P_{trade,Max} \quad (25)$$

$$0 \le P_L(t); 0 \le P_{DR}(t) \quad (26)$$

Where $P_{WPP}(t), P_{DR}(t), P_{trade}(t)$ refers to WPP power generation, amount of load decrease after DR, power trade with adjacent grid and $P_L(t), L(t)$ refers to load power before DR, load power after DR at t^{th} hour respectively.

5. Numerical Study

In this section, the impact of the suggested model is displayed through numerical case studies. A 30 MW wind farm, which consist of fifteen 2 MW commercial wind turbines, is considered. The wind data are fitted by the Sotavento wind farm, in Spain(23/02/2010) [16]. The conversion of wind speed to wind power data of Vestas turbine ($V80$, P_{Max} =2Mw) is shown in Table 1 and corresponding graph is shown in Fig. 3 [17]. The quantity of loads and the interrelated prices are conceded in Table 2 [18], assumed load is equal to 1% of load profile in this table. Wind power generation and load profile in test day is illustrated in Fig. 4. Sample grid consist of two busses where in bus one, wind farm and residential single periodic load is located in bus two, shortage of power is compensated by adjacent grid. This sample grid is illustrated in Fig. 5.

Table 1. Wind speed and power data (Vestas turbine -V80-Type)

Wind speed (m/s)	Power (Mw)	Wind speed (m/s)	Power (Mw)	Wind speed (m/s)	Power (Mw)
1	0.00	10	1.32	19	2.00
2	0.00	11	1.65	20	2.00
3	0.00	12	1.86	21	2.00
4	0.07	13	1.97	22	2.00
5	0.17	14	2.00	23	2.00
6	0.29	15	2.00	24	2.00
7	0.47	16	2.00	25	2.00
8	0.71	17	2.00	26	0.00
9	1.00	18	2.00	27	0.00

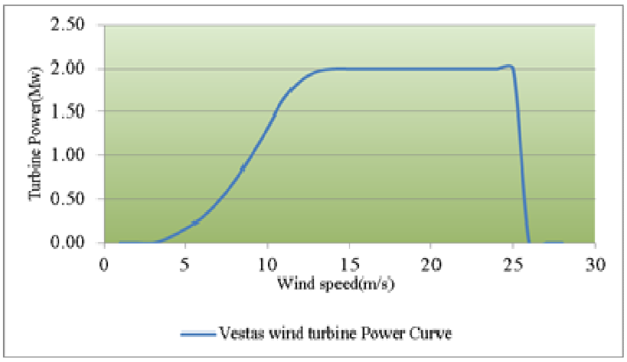

Fig. 3. Power curve of Vestas turbine (V80-Type)

Table 2. Load and price [18]

Hour	Load (Mw)	Price ($/Mwh)	Hour	Load (Mw)	Price ($/Mwh)
1	1700	18	13	2600	42
2	1600	18	14	2550	42
3	1700	18	15	2600	38
4	1700	18	16	2620	38
5	1750	18	17	2550	42
6	1820	18	18	2500	28
7	2000	24	19	2450	28
8	2400	24	20	2450	28
9	2550	42	21	2550	38
10	2600	38	22	2450	30
11	2650	43	23	2200	24
12	2600	42	24	1850	18

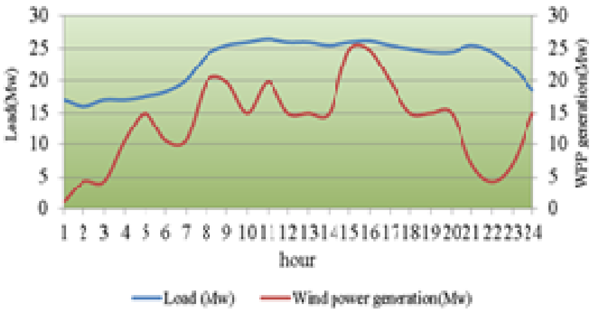

Fig. 4. Load and wind power generation

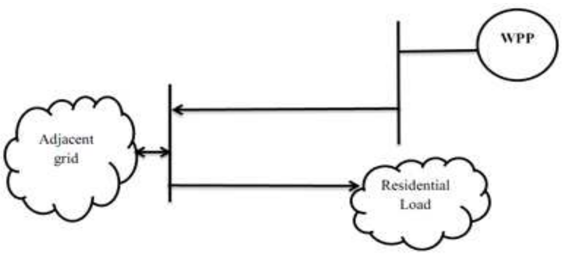

Fig. 5. Sample grid

Table 3. Initial wind power, load and revenue before DR

P_{Load} (Mw)	P_{WPP} (Mw)	Total Revenue($)
545	323.54	3949

The Table 3 shows initial situation of load (P_{Load}), wind power generation (P_{WPP}), and total revenue. All of these items are in 24 hours.

In this paper self-elasticity range is chosen between - 0.1 and -0.3based on data obtained from residential electricity demand by time-of-use pricing experiments [19].

5.1 Scenario I: revenue based on TOU

In this scenario TOU programs effect on MOs revenue and decrease of the load is studied and the results are presented in Table 4, This Scenario shows that for elasticity e = -0.1, e = -0.2, e = - 0.3, the decrease of load is 1.8%, 3.7% and 5.7% respectively. Also the increase in MOs revenue is 23%, 33% and 43% respectively.

Whit reference to Fig. 4 three time intervals are defined: from 8:00 am to 22:00 pm. peak period, from 1:00 am to 7:00 am as valley period, and 7:00 am to 8:00 am and 23:00 pm. to 1:00 am as off-peak period. And also, based on price curves [10], 18$/MWh, 30 $/MWh and 42 $/MWh are considered as the price in valley, off-peak and peak periods, respectively. We assumed that all the customers would participate in TOU program and all of them are single period load. As shown in Fig. 6 and Fig. 7 the MOs revenue is increased and load profile is decrease after implementing DR. This rise in MOs revenue and decrease in load improves with increase the elasticity. Hence this policy is beneficial for MOs.

Table 4. Impact TOU program on load and revenue

Load Before DR(Mw)	Elasticity	Load after DR (Mw)	Revenue Before DR($)	Revenue After DR($)	Load Decrease (%)	Revenue Increase(%)
545	- 0.1	538.28	3949	4884	1.8%	23%
545	- 0.2	531.66	3949	5269	3.7%	33%
545	- 0.3	525.04	3949	5654	5.7%	43%

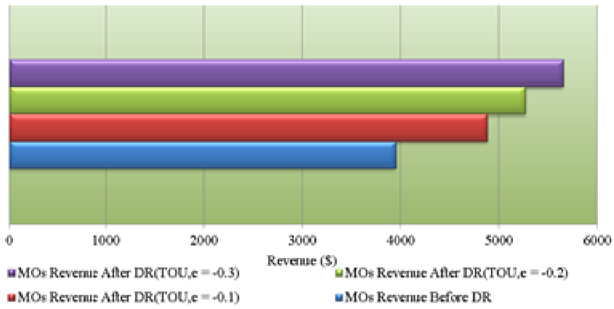

Fig. 6. Scenario I: Comparison plot of MOs revenue

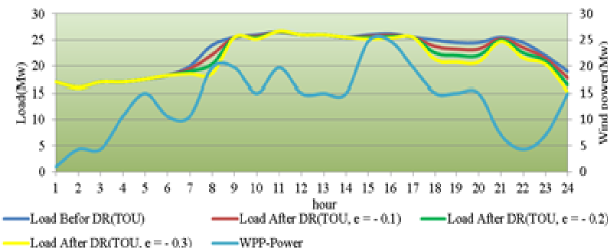

Fig. 7. Scenario I: Comparison plot of load decrease

5.2 Scenario II: revenue based on DLC

In this scenario DLC program effect on MOs revenue and decrease of load is studied and the results are presented in Table 5. This is by various DLC regimes with special incentives supplied by the local MOs for variety wind speed. Three incentive regimes were used in the simulations are as follow:

✓ Low wind speed period $(V_W \leq V_C)$ with Incentive $\mathrm{A(t)}$:

$$A(t) = (90\%) \bullet \rho(t) \tag{27}$$

✓ Medium wind speed period $(V_C \leq V_W \leq V_r)$ with incentive $\mathrm{A(t)}$:

$$A(t) = (20\%) \bullet \rho(t) \tag{28}$$

✓ High wind speed period $(V_r \le V_W \le V_{Co})$ with incentive $A(t)$:

$$A(t) = (0\%) \bullet \rho(t) \tag{29}$$

This scenario shows that for elasticity, e=−0.1, e=−0.2 and e=−0.3 the decrease of load is 2%, 5% and 7% respectively. Also the increase in MOs revenue is 7%, 14% and 21% respectively.

Table 5. Impact DLC program on load and revenue

Load Before DR(Mw)	Elasticity	Load after DR (Mw)	Revenue Before DR($)	Revenue After DR($)	Load Decrease(%)	Revenue Increase(%)
545	- 0.1	532.91	3949	4220	2%	7%
545	- 0.2	520.92	3949	4491	5%	14%
545	- 0.3	508.94	3949	4762	7%	21%

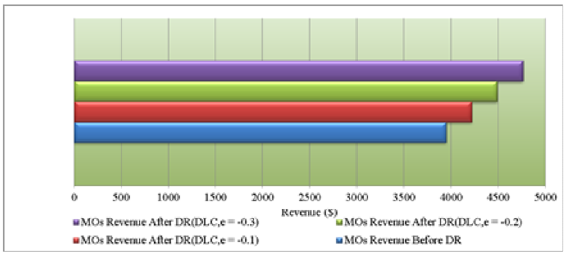

Fig. 8. Scenario II: Comparison plot of MOs revenue

As shows in Fig. 8 and Fig. 9 the MOs revenue is increased and load profile is decreased after implementation DLC program. This rise in MOs revenue and decrease in load improves with increase in elasticity.

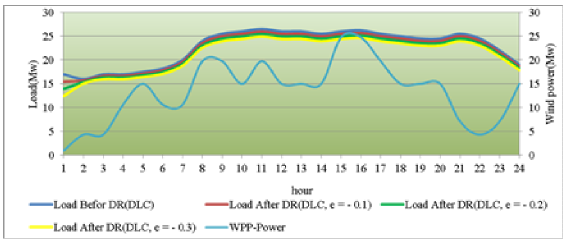

Fig. 9. Scenario II: Comparison plot of load decrease

5.3 Scenario III: Revenue Based on TOU and DLC Together

In this scenario TOU and DLC programs effect on MOs revenue and decrease of load is studied and the results are presented in Table 6. This scenario shows that for elasticity, e=-0.1, e=-0.2 and e=-0.3 the decrease of load is 2%, 9% and 14% respectively. Also the increase in MOs revenue is 31%, 47% and 64% respectively.

Table 6. Impact of TOU&DLC programs on load and revenue

Load Before DR(Mw)	Elasticity	Load after DR(Mw)	Revenue Before DR($)	Revenue After DR($)	Load Decrease(%)	Revenue Increase(%)
545	- 0.1	534.56	5492	6880	2%	31%
545	- 0.2	523.83	5492	7660	9%	47%
545	- 0.3	513.30	5492	8429	14%	64%

As shows in Fig. 10 and Fig. 11 the MOs revenue is increased and load profile is decreased after implementation DR with TOU & DLC together. This rise in MOs revenue and decrease in load improves with increase in elasticity. Hence the DR program with TOU & DLC together is more beneficial compared the DR policy with TOU and DLC only for MOs.

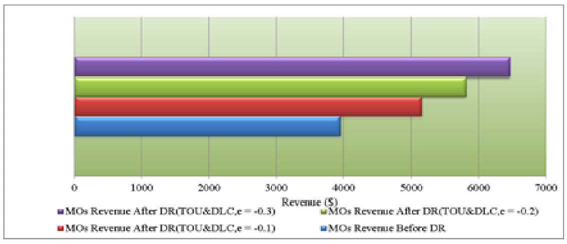

Fig. 10. Scenario III: Comparison plot of MOs revenue

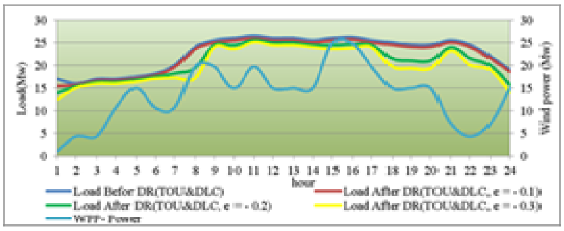

Fig. 11. Scenario III: Comparison plot of load decrease

6. Conclusion

This paper presents a novel framework to make wind power a more flexible energy source by using demand response programs. Three scenario studies investigated are TOU alone, DLC alone and TOU and DLC together. The results show demand response as an efficient factor for increasing MOs revenue and decreasing some of the load in special conditions. Therefore DR could smooth the output of wind generation in intervals of one hour, which will result in flexibility of wind generation to participate in the electricity market. DR with TOU and DLC together is more effective compared to DR with TOU alone and DR with DLC alone.

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