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Design an Optimal Demand Response Program to Alleviate the Undesirable Effects of Wind Uncertainty in Operation of the System

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Abstract: Today, Demand Response (DR) has become a promising concept in operation of power systems. In this study, a new model is proposed for optimal design of Real-Time Pricing (RTP) demand response. The goal of this program is to reduce undesirable effects of fluctuations and uncertainty of wind power generation in the power system. The employed model for demand response is an efficient model based on obtaining maximum profit by the customer. To this end, optimal prices of RTP are obtained through solving an optimization problem. The proposed objective function for this problem includes production cost, reserve cost, expected cost of unsupplied power and payments of responsive loads participating in RTP. In the proposed model all power flow constraints and constraints of unit commitment are considered. In addition, uncertainty of wind power generation considering several scenarios is well modeled. In order to analyze the proposed model, IEEE Reliability Test System (RTS) is used as a case study. The proposed optimization problem is a mixed integer nonlinear problem which has been modeled and solved by GAMS. The simulations are performed in three cases and its results are analyzed and compared. In the first case, wind resource and responsive loads are not considered, wind resource is present in the second case and in the third case and wind resource and responsive loads are both considered. Simulation results show that RTP program can eliminate unsupplied power and it reduces operation costs in power system including wind farm.

Key words: Demand response, wind farm, uncertainty, real-time pricing, power generation, optimization problem

INTRODUCTION

In recent years, using renewable energies including wind and solar in power systems has increased significantly, amidst wind energy plays a more effective role in generating electricity compared to other renewable resources. In fact, considering nature of wind being free and that it reduces air pollution, most countries have put utilization of wind farms in their priority list. Besides mentioned advantages, using these resources causes some problems in power systems because wind energy is random and variable. In fact, amount of wind power might be different from what is predicted and planned in some hours of the day.

Although, resources provided by thermal units is applied as the first approach of exploiters for system security maintenance and covering uncertainty of wind power but these resources create problems among which extra production units commitment and utilizing units in output less than optimal point can be mentioned. The greater is the difference between values predicted for wind farm power and real values, exploiters have to reserve a greater portion of production capacity and more costs are imposed on them.

Considering these problems, exploiters can reduce customer's consumption instead of increasing production, when they face production shortage caused by error in wind prediction and balance production and consumption. This resource on demand side which can compete with production lies in demand response concept. Demand response as a potential solution plays an important role in problems associated with reducing problems of integrating renewable energies. Today, demand response programs have attracted attentions due to peak reduction, increase in economic utilization and reduction of reserve requirements.

In this study, a new model is proposed for optimal design of a real-time pricing DR with the purpose of reducing undesirable effects of fluctuation and uncertainty of wind power production in power system based on obtaining maximum profit by the customer. To this end, optimal prices for RTP are obtained through solving an optimization problem.

Literature review: By Wang *et al.* (2003), a market model is introduced in which producers and consumers can offer their suggestions as five individual products including energy, up spinning reserve, down spinning reserve and two types of stand-by reserve which not only increases consumer's profit but also decreases business power of producers. Xie *et al.* (2009) has tried to encourage consumers to change electricity consumption pattern through price signals using price-based DR when system has problems caused by low wind blow. Therefore, in

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such situations, using plant reserves is less required. In this reference, load per hour is considered as a function of price which shows different behavior from considering price in each hour. By Parvania and Fotuhi-Firuzabad (2012), load reduction of consumers who have offered their proposal to next day market is used for changing system's load shape. Parvania and Fotuhi-Firuzabad (2012) have used a one-step market clearing and have considered consumer's load reduction along with plant's spinning reserve.

Papavasiliou and Oren (2014) has evaluated costs imposed on the system caused by wind power uncertainty in 3 different cases. Papavasiliou and Smeers (2015) which is implemented on a wind and DR study in Germany, a multi-stage random plan is used for specifying long-term and real-time market balance and multi-stage random model is proposed by real time market for analyzing effect of consumption curves on next day markets. Li *et al.* (2015), a random model is proposed for planners to defend against uncertainty of wind farms. In this reference, uncertainty of load prediction and output power are well considered. Other factors considered in the model include regulatory output rate of transmission lines and generators. Sioshansi and Short (2009), used a RT-DR program for production planning. And the results confirm that RTP increases wind penetration and load provided by wind production, effectively. Sioshansi (2010), Sioshansi and Short (2009) a model is proposed for simulating performance of power systems under high penetration scenarios which can be used for evaluating costs of wind resource prediction errors. Simulations show that, if an error occurs in wind prediction, system costs would increase. Moreover, RTP might decrease integration and load loss costs. Next study presents our proposed model.

MATERIALS AND METHODS

In optimal design of RTP-DR, electricity price for low peak, off-peak and peak hours are optimized for reducing undesirable effects of wind farms in system utilization.

Study components: Cost function of thermal units in this study is modeled as a second order function. In the following, main constraints of thermal units, demand response and wind production scenario are presented.

Allowed range of production units: Output power of each generator should not exceed its nominal value and it should not also be less than threshold of steam boiler utilization. Allowed constraint of production units are defined in Eq. 1 (Sun *et al.*, 2014):

$$P_i^{min} \le P_i^{max} \le P_i^{max} \tag{1}$$

Where:

P_i^{min} = Minimum Production of thermal units (MW)
P_i^{max} = Maximum Production of thermal units (MW)
P_i = Production Power of thermal units (MW)

Increasing and decreasing production power constraints: Variation rate of power produced by a unit cannot exceed a certain value. This constraint is defined in Eq. 2 and 3:

$$P_i(t)\text{-}P_i(t\text{-}1) \le RUR_i \tag{2}$$

$$P_i(t\text{-}1)\text{-}P_i(t) \le RDR_i \tag{3}$$

where, RUR_i and RDR_i represents power up and down rates of the i generator (MW/h), respectively.

Minimum on and off times constraint: For thermal preservation of stator and rotor when a thermal unit is turned on a minimum time is considered for its connection to the network. Similarly, when a unit is turned off, a minimum off time is considered. This constraint is defined in Eq. 4 (Tseng *et al.*, 2000):

$$U_i(t) = \left\{\begin{array}{lll} 1 & \text{if} & -1 \le x_i(t-1) < t_i^{on} \\ 0 & \text{if} & -1 \ge x_i(t-1) > -t_i^{off} \\ 0\text{or}1 & & \text{Otherwise} \end{array}\right\} \tag{4}$$

Where:

$U_i(t)$ = Binary variable showing off and on time of ith unit in time t
$x_i(t\text{-}1)$ = Off/on time of ith unit till t-1 (h)
$t_i^{on}(t_i^{off})$ = Minimum time that ith unit should remain on/off after being turned on/off (h)

For logical performance of binary value mentioned above, Eq. 5 and 6 are proposed:

$$y_{i\,(t)+z_i\,(t)} \le 1 \tag{5}$$

$$u_i(t)\text{-}u_i(t\text{-}1) = y_i(t)\text{-}z_i(t) \tag{6}$$

Where:

u_i = Binary variable for ith unit to be on (1 unit is on, 0 unit is off)
y_i = Binary variable of ith unit to be turned on (1, unit is turned on otherwise, 0)
z_i = Binary variable of ith unit to be turned off (1, unit is turned off, otherwise, 0)

Maximum production in turn on times and time before turn off: In order to prevent significant changes in temperature of generator body in short times, maximum production in turn on times and time before turn off constraint is applied which is a combination of up and down production power as Eq. 7 and 8 (Aminifar and Fotuhi-Firuzabad, 2007):

$$\begin{aligned}\bar{P}_i(t) \leq P_i(t-1) + RUR_i u_i(t-1) + \\ SU\left[u_i(t) - u_i(t-1)\right] + P_i^{max}\left[1 - u_i(t)\right]\end{aligned} \quad (7)$$

$$\begin{aligned}\bar{P}_i(t-1) - P_i(t) \leq RDR_i u_i(t) + \\ SD_i\left[u_i(t-1) - u_i(t)\right] + P_i^{max}\left[1 - u_i(t-1)\right]\end{aligned} \quad (8)$$

Where:

$\bar{P}_i(t)$ = Maximum accessible output Power of ith unit in t (MW)

SU = Maximum producible power in turn on time (MW)

SD = Maximum producible power before turn off (MW)

Demand response models: In Eq. 9, a model is used for describing demand responses. This model is based on maximizing profit function of price-sensitive customers and an efficient model for customers participating in DR programs. Energy cost paid ($) is calculated as in Eq. 10 (Aalami *et al*., 2010a, b; Wang *et al*., 2003):

$$d_e(t) = \gamma \cdot d_0(t) \cdot \left\{1 + \sum_{k=1}^{T} E(t,k) \cdot \frac{\rho(k) - \rho_0(k)}{\rho_0(k)}\right\} \quad (9)$$

$$f_{1e} = (1-\gamma)\sum_{t=1}^{T} \rho_0(t) \cdot d_0(t) + \sum_{t=1}^{T} \rho(t) \cdot d_e(t) \quad (10)$$

Where:

γ = Participation of subscribers in RTP-DR programs (%)

$d_e(t)$ = Consumption of price sensitive subscribers in hour t after executing program (MWh)

$d_0(t)$ = The total predicted consumption for hour t before executing the program (MWh)

E (t, k) = The price reach of hour t relative to hour k

$p(t)$ = Electricity price in hour t ($/MWh)

$p_0(t)$ = The initial price in hour t ($/MWh)

Wind production scenario: Previous researches showed that wind speed specifications have maximum relation with Weibull distribution function in a particular location.

Therefore, here it is assumed that wind speed includes Weibull distribution function of mean predicted wind speed. Probability density function of wind speed is as follows (Tseng *et al*., 2000):

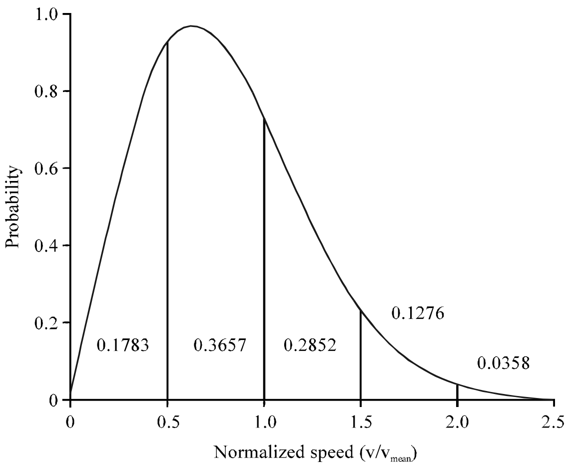

Fig. 1: Discretized curve of wind speed probability distribution; k = 2, c = $v_{mean}/0.9$

$$f(v) = (k/c)(v/c)^{(k-1)} e^{-(v/c)k},\ 0 < v < \infty \quad (11)$$

where, v, k and c represent wind speed (m/sec or miles/h), shape factor (dimensionless) and scale factor (it shares the unit of v), respectively.

For simplicity, wind speed distribution is normalized using weibull distribution mean speed. Probable points of v_{mean} increase with a constant step until maximum of the distribution is encompassed.

Therefore, wind speed distribution curve can be discretized in specific spaces where the number of intervals depends on the accuracy. Probability of each interval can be calculated using a numerical integral with GAMS. In this study, a 5-interval wind speed distribution is employed as shown in Fig. 1.

According to wind speed distribution curve and transforming speed to power function, wind turbine power is obtained. In this study, speed to power transformation function is as follows (Aalami *et al*., 2010a, b; Effatnejad, 2010):

$$S = \left\{\begin{array}{ll} 0, & \text{for } v_i \text{ and } v>v_0 \\ S_r(v-v_i)/(v_r-v_i), & \text{for } v_i \leq v \leq v_r \\ s_r, & \text{for } v_r \leq v \leq v_0 \end{array}\right\} \quad (12)$$

where, S, S_r, v_i, v_r and v_0 represent wind turbine output power (kW), rated power, cut-in wind speed, rated wind speed and cut-out wind speed, respectively.

Proposed objective function: Equation 13 represents the objective function of the problem which aims to minimize total cost of the system:

$$\text{Min}\left[\begin{array}{l}\sum_{t=1}^{NT}\sum_{i=1}^{NG}(F_{c,i}(P_{i,t})+SU_{i,t}+SD_{i,t})+\\ \sum_{w=1}^{NW}\text{Prob.}^{w}\left[\sum_{t=1}^{NT}(Ls(w,t)\times VOLL)\right]+\\ \sum_{t=1}^{NT}\sum_{i=1}^{NG}F_{c,i}^{r}(R_{i,t})-f_{le}\end{array}\right] \qquad (13)$$

Where:

NT = The Number of hours in planning horizon

NG = The Number of thermal units

$F_{c,i}$ = The cost function of thermal unit production ($)

$P_{i,t}$ = The Production of ith unit in hour t (MW)

$Su_{i,t}$ = The driving cost of ith unit in hour t ($)

$Sd_{i,t}$ = The cost of turning off ith unit in hour t ($)

NW = The Number of scenarios

$Prob^{w}$ = The Probability of wih scenario

$LS(w, t)$ = Load Lost in scenario w in hour t (MW)

$VOLL$ = The Value Of Lost Load ($/MWh)

$F^{r}_{c,i}$ = Reserve provision cost function of ith thermal unit ($)

$R_{i,t}$ = Reserve provision ith unit in hour t (MW)

f_{le} = Energy cost paid ($)

First row in Eq. 13 includes production cost of thermal plant plus driving cost and cost of turning them off and cost of lost loads in scenarios. Second row includes cost of reserve provision from thermal plants and DR costs.

RESULTS AND DISCUSSION

In order to simulate the proposed method, a standard 24-bus IEEE system is studied. In order to investigate the proposed model, simulation is performed in 3 stages, so that, effect of all components are specified. First, optimal load distribution without DRs and wind resources is studied. Second, wind resources are added to the network to determine their effects on the network and finally DRs are added to the model.

In order to minimize costs, designing optimal DRs including proposed cost for consumption hours is considered unknown which is described in the following. Consumption distribution of this study is presented in Table 1.

Model without wind resources: In order to begin, unit commitment and economic load distribution is executed for a 24 h horizon. In next steps, wind resources and RTP-DRs without knowing the hourly prices are added to the model. Total production graph without wind resources are shown in Fig. 2. In order to perform a numerical comparison, total cost results.

Model with wind resources: In this study, wind resources are added to the model. For this purpose, a 400 MW wind farm is replaced with the 350 MW generator of bus 23. Number of considered scenarios in this study is 5 and probability of these scenarios is according to the following Table 2.

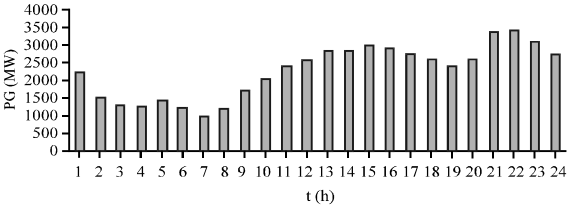

Fig. 2: Total production of units throughout a day without wind resources (MW)

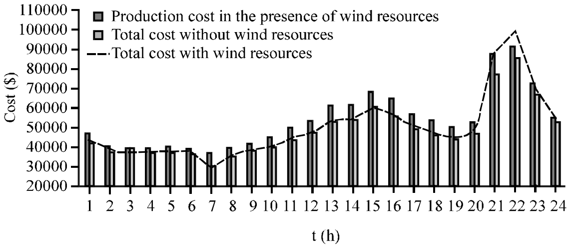

Fig. 3: Production cost and total cost throughout a day with and without wind ($)

Table 1: Consumption Distribution in 24 h (%)

Hours	Distribution (%)
1	65
2	44
3	38
4	37
5	42
6	36
7	28
8	35
9	50
10	60
11	70
12	76
13	83
14	83
15	87
16	85
17	80
18	76
19	70
20	75
21	98
22	100
23	90
24	80

Figure 3 compares production cost and cost of totala units throughout a day in the presence of wind resources and without wind resources in dollars.

As shown in Fig. 3, production cost in the presence of wind resources is less than total cost without wind resources. It should be noted that total cost in the

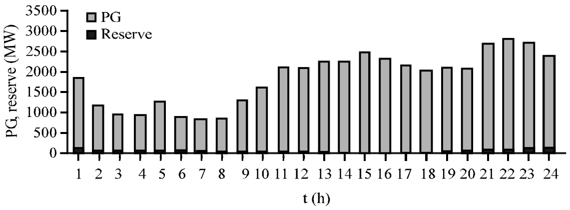

Fig. 4: Total production and reserve of units in the presence of wind resources (MW)

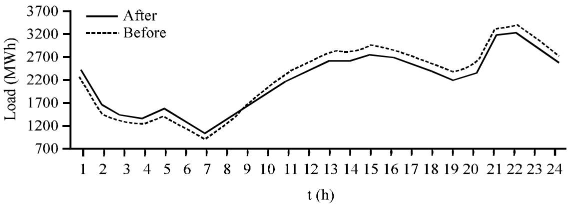

Fig. 5: Consumed load before and after executing DR program (MWh)

Table 2: Probability of wind scenarios

Scenario	Probability
1	0.395991
2	0.262024
3	0.160696
4	0.091350
5	0.048136

Table 3: Load profile

Load profile	Hours
Low peak	1-8
Off-peak	9-20
Peak	21-24

presence of wind resources is less than total cost without wind resources except at 9 and 10 p.m. which are peak hours. This cost increase is due to reserve and outage penalties considered in total cost.

Since, outage penalty is high, only in peak hours where there is no other way than disconnecting load, some part of load is disconnected. Load disconnection at 9 and 10 p.m. is calculated as 87.98 and 125.83 MW. Outage penalty in these hours is 21291$. Total production and reserve throughout a day in this study is shown in Fig. 4.

Total production of this study in the presence of wind resources compared to the case where wind resources are not present has decreased about 16.3%. According to Fig. 4 no reserve is assigned between hours 13-18. This might be due to wind resource production as mandated in hours considering exact predictions in scenarios in these hours.

Model in the presence of wind resources and DRs: In this study, the proposed model is like system proposed. With this difference that 20% of total load is considered as price responsive. Load profile of demand responses include low peak, off-peak and peak hours according to Table 3 self and cross lasticities are also presented in Table 4. Before investigating effect of DR program, optimal designed hour price (k) is presented in Table 5. Base price of subscribers is 3 $/MWh. Load amount after executing the program for comparing with load before executing the program is shown in Fig. 5.

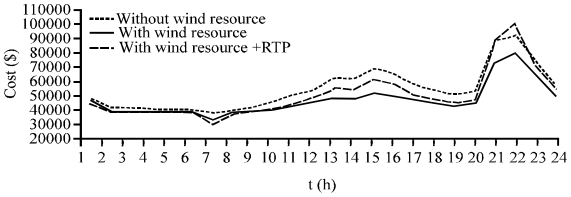

Fig. 6: Comparing total cost in this study throughout a day ($)

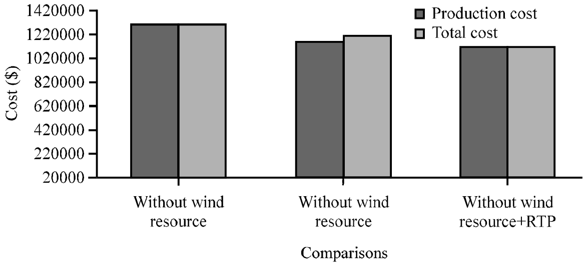

Fig. 7: Comparison of total cost and production cost in three study sections ($)

Table 4: Self and cross elasticities (Wang and Gooi, 2011)

Low peak	Off-peak	Peak
-0.1	0.010	0.012
0.01	-0.100	0.016
0.012	0.016	-0.100

Result of 20% participation of subscribers in RTP program is shown in Fig. 5. In this situation, load peak has decreased about 6.2%. If wind resource production is less than mandated amount, electricity price is increased, so that, less DR is consumed. In addition, if wind production exceeds mandated amount, price of DRs in decreases such that consumption is increased and production and consumption are balanced. Figure 5 shows that price in low peak hours is decreased and subscriber's consumption is more than predicted amount. But in off-peeak and peak hours which price in increased, consumption is less than predicted amount.

Considering the model in the presence of wind resources and DR program, no outage has occurred. Figure 6 compared total cost throughout a day in all 3 section of this study.

As can be seen in Fig. 6, total cost after executing RTP program has reduced significantly compared to

Table 5: Hourly designed prices

Hours	1	2	3	4	5	6	7	8
$/MWh	1.4154	1.3739	1.4355	1.3689	1.3386	1.3728	1.4075	1.4625
Hour	9	10	11	12	13	14	15	16
$/MWh	3.9188	3.9571	3.7453	3.7111	4.1676	3.5241	3.6107	3.2776
Hour	17	18	19	20	21	22	23	24
$/MWh	4.0096	3.7289	3.4765	3.9346	4.5546	4.5033	4.7986	4.8295

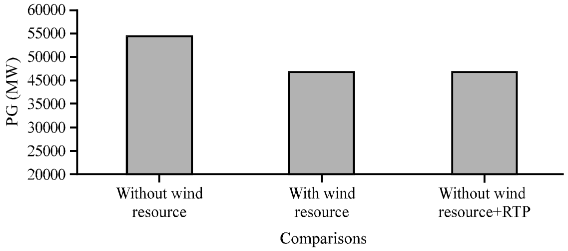

Fig. 8: Comparison of total cost in 3 case studies (MW)

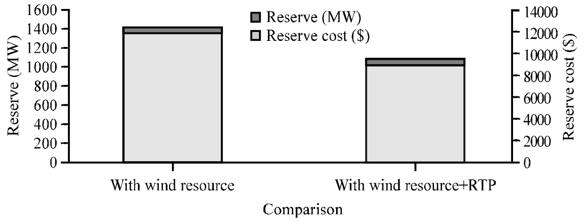

Fig. 10: Comparing reserve and reserve cost in all 3 case studies (MW/$)

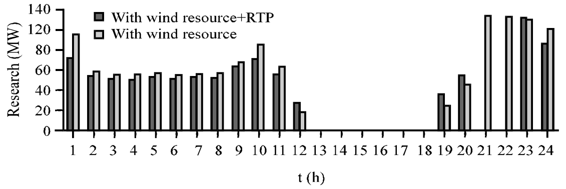

Fig. 9: Comparison of reserve throughout a day in the presence of wind resources and RTP and in the presence of wind resources only (MW)

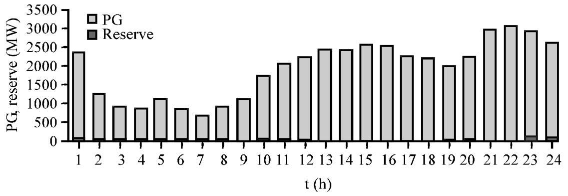

Fig. 11: Total production and reserve throughout a day in the presence of wind resources and DRs (MW)

other two cases. In addition, comparison if total cost and production cost for all three sections is according to Fig. 7.

Reduction of total cost after execution of DR program is estimated as 14.1% compared to base study and 7.1% relative to the case study in the presence of wind resources. Figure 8 compares total cost of units for all three case studies.

According to Fig. 8, maximum production is related to the case where wind resources are not present, case in which wind resources are present and case where both wind resources and RTP are present, respectively. Comparison of reserve throughout a day in cases where wind resources and RTP program are present and case where wind resources are not present is shown in Fig. 9.

According to Fig. 9, studying the presence of wind resources and DRs, requirement to reserve in hours 21 and 22 has been resolves which be due to creating balance between production and consumption of using DRs. Reserve and reserve cost for all two case studies are shown in Fig. 10.

Figure 10 shows that reserve cost and reserve after using DRs have decreased; this reduction in reserve cost is about 23.03%. Figure 11 shows total production of units throughout a day in the case where wind resources and DRs are present. As shown in Fig. 11, compared to other case studies, reserve has decreased in some hours.

CONCLUSION

In this study, a new model is proposed for determining optimal prices of RTP demand response program in a system with considerable penetration of wind resources. To this end, self and cross lasticities in low peak, off-peak and peeak and economic model of DR program is used. Simulation is performed on a standard 24-bus IEEE system and the results are evaluated. According to simulation results, in the case where wind resources are present, total cost has decreased d, except at 9 and 10 pm where cost has increased due to outage penalty. In addition, in the case where wind resources and DR program are present load peak has decreased about 6.2%. RTP has decreased the requirement for outage and reserve. Furthermore, total cost after executing DR has decreased compared to previous cases. According to the obtained results, RTP has a significant impact on system flexibility and provides better management of wind resources in utilization of power systems. Optimal design of RTP based on desirable economic model and considering utilization condition of the system, this demand program would be developed more. Therefore, RTP might be an effective approach for increasing wind penetration in the system and increasing provided load.

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