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Optimal operation of power system incorporating wind energy with demand side management

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KEYWORDS

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Abstract The high penetration of the wind energy in the power systems raises some issues such as ramping and mismatch between the wind power and power demand. One of the possible solutions to these issues is the demand side management (DSM). In this paper, dynamic economic dispatch (DED) incorporating different penetration levels of wind energy and utilizing the DSM is proposed to solve the issues related to high penetration of wind energy. The effect of utilizing the DSM on the operation cost with different test cases is discussed. The General Algebraic Modeling System (GAMS) using BARON as a solver and genetic algorithm (GA) with hybrid function are used to solve the proposed DED model and a comparison between them is assessed. The proposed model is applied to a six units' generation system to test the effectiveness of the proposed model.

1. Introduction

In Egypt most electricity is generated from electric power stations that use natural gas. The government decided to increase the generation from renewable energy, such as wind energy, to reach 20% at 2020. The wind energy has a lot of advantages which are clean and low running cost, however it has some disadvantages as the wind energy resources are intermittent in nature. As a consequence of high wind penetration, some issues must be widely studied which are as follows:

- Comprehensive focus on system planning and load forecasting.
- The inadequate correlation between the wind power and the load (power balancing issue).
- Ancillary services requirements such as faster ramp rates resources.
- Power quality issues such as voltage variations, voltage fluctuations and harmonics.

To solve these issues the electrical power system needs to be more flexible to respond to the instantaneous fluctuations in both load and renewable generation [1]. This paper will focus on two issues from the above list which are power balancing issue and high ramp rates issue.

Energy storage and demand side management (DSM) or demand response (DR) are common flexible resources that show compatibility with wind power. All of them have been known as effective resources to integrate wind power; however, the experience in doing that remains limited. Energy storage

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and DR present reasonably quick response in shifting or clipping the load because of their flexible characteristics. Energy storage and DR are quiet not extensively installed on the power system (with the exception of pumped hydro storage) and need additional consideration of their importance to widely install them in power systems [2]. As an example of utilizing a storage system to mitigate the wind variability, the system proposed in [3], in which a wind power smoothing system that uses an optimization algorithm to reduce the variability of wind energy, is introduced. In [4], a dispatch strategy is proposed which allows the battery capacity to be determined so as to maximize a defined service lifetime/unit cost index. Besides, it shows how to yield the short term wind farm output power schedule which meets the specified confidence level of power delivery commitment.

There is a lot of research work that incorporate the DSM for different objectives such as the economic evaluation of (DR) through a mathematical model [5]. The objective is to find the fair value of the DR in mitigating the intermittent effects of the wind power. In [6], the DSM is utilized through two options which are peak clipping and demand shifting in a unit commitment problem to study the impact of high wind penetration on operation and cost savings from the use of DR. A day-ahead network constrained market clearing formulation considering DR is suggested in [7]. It is concluded that this model can introduce flexibility into the load profile; less dependence on ramp up/down services by the conventional generators and increases the penetration of wind energy. In [8], a dynamic economic dispatch (DED) model is proposed having both thermal and wind generators. In this model, normally distributed random variables have been considered for the wind speed and load forecast errors. The DED model gives valuable information for reliable, safe, and economic operation of power systems. In [9], bio-diesel engines are used for compensation of the intermittent wind energy and solving ramp rate issue with wind energy. Real-time pricing (RTP) in case of high wind penetration has been utilized to decrease the re-dispatch costs and cancel loss of load events [10,11]. Besides, the results conclude that hosting wind and RTP into a market can result in a big surplus gains which will push electricity demand to respond to actual wind resource availability. Demand dispatch and probabilistic wind power forecasting is used to enhance the operation of electricity markets incorporating a high penetration of wind power [12]. A stochastic optimization model for the day-ahead scheduling in power systems, with the hourly DR for managing the intermittency of renewable energy sources has been introduced in [13]. The analysis of the impact of DSM, with the aim of enabling the integration of the growing intermittent resources in Portugal, has been discussed in [14].

In this paper, the solution for some of the issues related to the high penetration of wind energy such as load balancing difficulties and ramping problems has been discussed showing the importance of using DSM to solve these issues and the consequences for not using it. A DED model incorporating different penetration levels of wind energy is applied and the load shifting is implemented by using the DSM to solve the issues related to the high penetration of wind energy. The comparison between different cases has been demonstrated by using the DSM for shifting the shiftable loads and without using the DSM. Different load profiles such as summer and winter loads have been addressed and finally different participation levels from consumers and their effects on the results have also been addressed. GA with hybrid function and GAMS using BARON as a solver have been used as optimization techniques to solve the DED problem with different scenarios. It shows that both are almost giving nearly the same results, but GAMS is faster than GA, therefore the GAMS will be chosen for solving the DED model.

Full description of the dynamic economic dispatch and demand side management approaches is introduced in Section 2, the case study based on a system consisting of six thermal generators and one wind farm is fully described in Section 3, the discussion of the results are presented in Section 4, and conclusions are finally drawn in Section 5.

2. Modeling approaches

2.1. Dynamic economic dispatch (DED)

Optimal operation of electric power system networks is a challenging real-world engineering problem. The dynamic economic dispatch (DED) occupies a prominent place in power system's operation and control. The goal of DED is to determine the optimal power outputs of online generating units in order to meet the load demand satisfying various operational constraints over finite dispatch periods. The DED considers additional practical constraints such as upper and lower bounds on the units' ramping-rates. In reality, units will not respond to steep or instantaneous load variations.

In the proposed DED optimization problem, the cost of operation will be minimized through the day as given in Eq. (1) and subjected to the different constraints which are as follows: the load balance as given in Eq. (2) where the wind power can be utilized as any value between zero and the maximum forecasted wind power as in Eq. (3), loss value as given in Eq. (4), minimum and maximum generation capacities as shown in Eq. (5) and ramping up and down constraints as given in Eqs. (6) and (7) [15].

Minimize:

$$C_{op} = \sum_{t=1}^{T} \sum_{g=1}^{G} C_{gt}(P_{gt}) = \sum_{t=1}^{T} \sum_{g=1}^{G} a_g + b_g P_{gt} + c_g P_{gt}^2 \quad (1)$$

where C_{op} is the total operating cost, C_{gt} is the cost function of gth thermal generator during interval t, P_{gt} is the real power generated by generator gth during t interval, a_g, b_g, c_g are the cost coefficients of the gth generator, T is the number of dispatch intervals in the dispatch period and G is the total number of thermal generators.

Subject to:

$$\sum_{g=1}^{G} P_{gt} = P_{dem,t} - W_{P,t} + P_{Loss,t} \quad (2)$$

$$0 \leqslant W_{P,t} \leqslant W_{F,t} \quad (3)$$

where $P_{dem,t}$ is the total load demand without using DSM during t interval, $W_{P,t}$ is the wind power that can be utilized during t interval, $W_{F,t}$ is the forecasted power generated by the wind farm during t interval and $P_{Loss,t}$ is the transmission system losses during t interval.

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$$P_{Loss,t} = \sum_{g=1}^{G}\sum_{j=1}^{G} P_{gt}B_{gj}P_{jt} \quad (4)$$

where P_{gt}, P_{jt} are the real power injections at gth and jth buses at time t ($t = 1,2,\ldots,T$), respectively, and B_{gj} are the loss coefficients.

$$P_{g,\min} \leqslant P_{gt} \leqslant P_{g,\max} \quad (5)$$

where $P_{g,\min}$ and $P_{g,\max}$ are the minimum and maximum power which can be generated by generator gth respectively.

$$P_{gt} - P_{g(t-1)} \leqslant UR_{g,\max} \quad (6)$$

$$P_{g(t-1)} - P_{gt} \leqslant DR_{g,\max} \quad (7)$$

where $UR_{g,\max}$ and $DR_{g,\max}$ are the maximum up and down ramp rate limit of the gth generator respectively, $t = 2,3,\ldots,T$, and $g = 1,2,\ldots,G$.

2.2. Demand side management (DSM)

Almost all DSM programs are motivated by utilities. Utility based DSM is the planning, implementation, and monitoring of activities designed to encourage customers to adapt their level and pattern of electricity usage so that the load profile can be changed by the utility company, thus it can produce power in an optimal way. There are six load shape objectives of the DSM program as shown in Fig. 1 which are as follows: peak clipping, valley filling and load shifting as basic level and advanced levels such as strategic conservation, strategic load growth and flexible load shape [16].

Applying one or more of the DSM programs such as the time of use (TOU) rate can be utilized as a program to achieve a load shifting objective through offering high price during peak periods and low price in off-peak periods [16]. This shifting in loads will involve modifications to the DED model as a part of the demand which will be variable and specified according to the participation level and the number of shiftable appliances. The new demand will be the reference demand adding to it the upward demand and subtracting the downward demand from it as shown in Eq. (8).

$$P_{demnew,t} = \sum_{l=1}^{L} P_{dem,lt} + \sum_{e=1}^{E} P_{demup,et} - \sum_{e=1}^{E} P_{demdown,et} \quad (8)$$

where $P_{demnew,t}$ is the total load demand with DSM during t interval (after applying the DSM program to shift some of the shiftable loads), $P_{dem,lt}$ is the demand of each individual load, $P_{demup,et}$ is the upward demand variation of load e during t interval, $P_{demdown,et}$ is the downward demand variation of load e during t interval, L is the total number of all individual loads and E is the total number of shiftable loads only.

Some constraints for increasing and decreasing the demand of each individual load but not for all loads are found because some are non-shiftable as follows:

1. According to the proposed DSM program for shifting the shiftable loads, the increase and decrease of the demand should be balanced through the day as shown in Eq. (9).
2. The participation level of the customers, according to lot of previous studies not all customers will participate in the DSM program so there is a limit to increase or decrease the loads at each hour as shown in Eqs. (10) and (11).

$$\sum_{t=1}^{T} P_{demup,et} = \sum_{t=1}^{T} P_{demdown,et} \quad (9)$$

$$0 \leqslant P_{demup,et} \leqslant \alpha_{up,e} \quad (10)$$

$$0 \leqslant P_{demdown,et} \leqslant \alpha_{down,e} \quad (11)$$

where $\alpha_{up,e}$ and $\alpha_{down,e}$ are the maximum allowable upward and downward change in the demand of load e respectively ($e = 1,2,\ldots,E$).

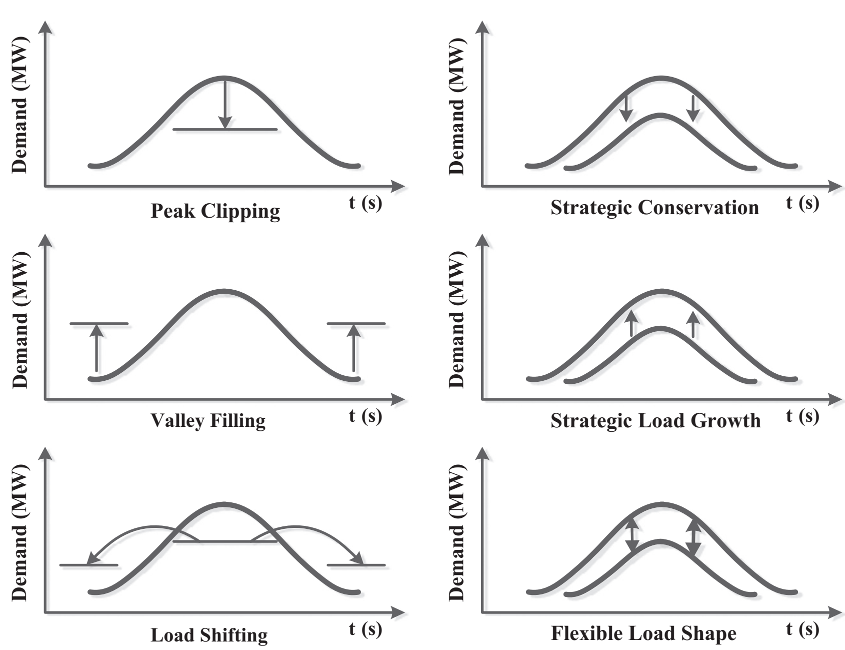

Figure 1 Load shape objectives for load management program.

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So, through the required new demand which will be an output of our approach, the TOU rate tariff should be designed carefully to encourage the consumers to follow the same profile. Upon adding the DSM constraints to the DED problem, the old demand given in Eq. (2) will be changed as given in Eq. (12).

$$\sum_{g=1}^{G} P_{gt} = P_{demnew,t} - W_{P,t} + P_{Loss,t} \quad (12)$$

where $t = 1, 2, \ldots, T$.

3. Case studies

Case studies are extensively carried out on a system consisting of six thermal generators and one wind farm. The details of the generators for the six units test system are found in Table 1 [17]. Fig. 2 shows the data of the wind farm power in a day as 10% of total generation (1 p.u.). In the case study, two penetration levels 10% and 20% have been studied. For DSM, three different levels of participation are considered including 5%, 10%, and 15% participation levels. The participation level gives the information about the expected percentage of participants in the DSM program so 15% means 15% of the total load can participate in the DSM program.

Fig. 3 gives the details of the total load in winter and summer; this total load includes residential, commercial and industrial loads. This paper supposes that only residential loads will participate in the DSM program. The residential loads percentage is in the range of 50% of total load, as in Egypt case [18]. The residential load consists of individual loads such as washing machines, dish washers, refrigerators, freezers, water heaters, water pumps, ovens, lighting, and other appliances. Air conditioner loads will be added in summer.

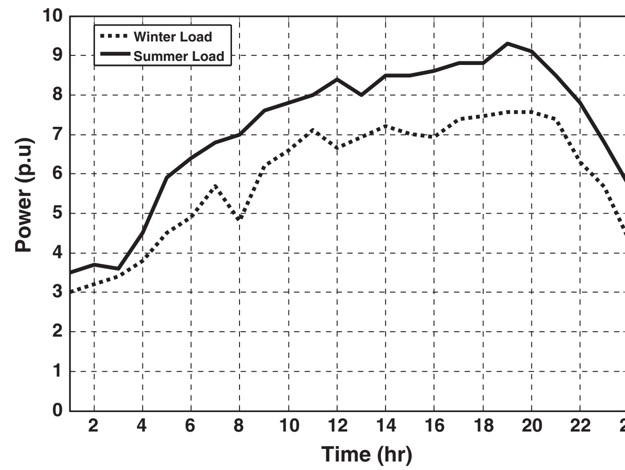

Figure 3 Total daily load in summer and winter.

The DSM program will only use the shiftable loads from the residential sector such as washing machines, dish washers, water heaters, and air conditioners to make the needed shift in the total load according to the participation level.

Table 1 Generators' limits and cost coefficients.

Generator g	Generator limit		Cost coefficients		
	$P_{g,\min}$ (p.u.*)	$P_{g,\max}$ (p.u.)	a_g ($/h)	b_g ($/MW h)	c_g ($/(MW)^2 h)
1	0.5	1.5	10	200	100
2	0.5	1.5	10	150	120
3	0.5	1.5	20	180	40
4	0.5	1.5	10	100	60
5	0.5	1.5	20	180	40
6	0.5	1.5	10	150	100

* The base of the per unit (p.u.) system is 100 MVA.

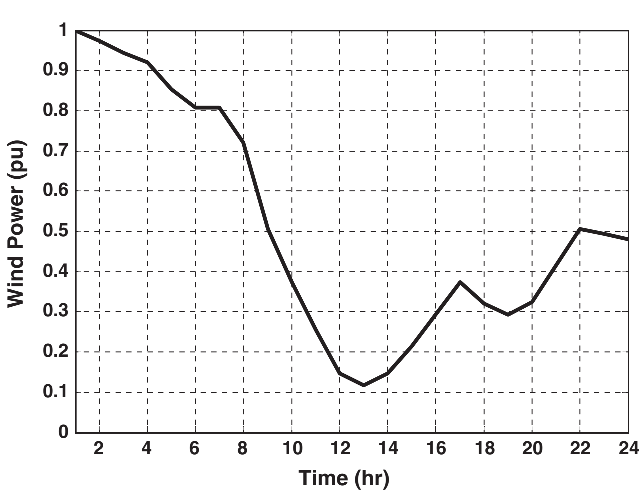

Figure 2 Wind power in a day.

4. Results and discussions

A number of scenarios such as changing the participation level of consumers and wind penetration level are applied for different load profiles in winter and summer using the DSM to solve some of the issues related to the high penetration of wind energy specifically ramping events that happen when the load decreases and the wind increases or vice versa and the mismatch between the high wind power and peak load.

Different scenarios have been addressed. Tables 2–5 give the output of the DED solutions under different cases. GAMS software using BARON as a solver and genetic algorithm with hybrid function (*fmincon)* are used for solving the DED problem. The results have showed that using GA with *fmincon* gives almost typical results like GAMS but needs repetitive iterations to reach the optimum solution and it also takes longer time than using GAMS. As an example, in case of the summer load with DSM and 15% participation level, the time taken by GAMS is 5 s, while GA with hybrid function

Table 2 Cost of operation of 10% penetration of wind and winter load.

Participation level/scenario (%)	Load without DSM ($)	Load with DSM ($)	Ramping in wind without DSM ($)	Ramping in wind with DSM ($)
5	32171.013	31896.411	32272.316	31992.040
10	32171.013	31668.192	32272.316	31739.948
15	32171.013	31463.072	32272.316	31507.602

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Table 3 Cost of operation of 10% penetration of wind and summer load.

Participation level/scenario (%)	Load without DSM and with 5% load shedding ($)	Load with DSM	Ramping in wind without DSM (with 5% load shedding) ($)	Ramping in wind with DSM
5	42503.237	–	42791.979	–
10	42503.237	–	42791.979	–
15	42503.237	41714.896$	42791.979	41931.426$

(–) means no solution for the DED problem.

Table 4 Cost of operation of 20% penetration of wind and winter load.

Participation level/scenario (%)	Load without DSM ($)	Load with DSM ($)	Ramping in wind without DSM ($)	Ramping in wind with DSM ($)
5	29857.568	29572.107	30039.566	29744.310
10	29857.568	29305.721	30039.566	29472.395
15	29857.568	29064.156	30039.566	29223.213

Table 5 Cost of operation of 20% penetration of wind and summer load.

Participation level/scenario (%)	Load without DSM and with 2.5% load shedding ($)	Load with DSM ($)	Ramping in wind without DSM (with 2.5% load shedding) ($)	Ramping in wind with DSM ($)
5	39578.484	39190.264	40012.610	39602.177
10	39578.484	38694.426	40012.610	39098.039
15	39578.484	38266.155	40012.610	38666.081

takes 15 min for each iteration and in some cases it takes more than one iteration to reach the optimum value (the processor is core i5 and the RAM is 4 MB).

As clearly shown in Table 2 (results of 10% wind penetration in a day in winter), without using the DSM the solution of the DED problem gives a constant value for the cost of operation which is 32171.013$ regardless of the participation level because there is no DSM program. However when using the DSM program to shift some of the shiftable loads, the cost will vary in accordance with the participation level so when the participation level increases the operation cost will decrease. In case when the wind causes a high ramping up or down exceeding the ramp rate limit of the thermal generators, the utilized wind energy will be less than the case of no ramping as clearly shown in Figs. 4 and 5, so the total operation cost will be high in case of high ramping exists. The use of DSM will add more flexibility to the system as through increasing the utilization percentage of wind energy as clearly shown in Fig. 4 in accordance with that the total operation cost will obviously decrease, and the lowest operation cost was for the 15% participation level.

Table 3 (results of 10% wind penetration in a day in summer) shows more obviously the issue that the high peak load does not match with the high value of wind power. It is clear that without using DSM or load shedding, the problem will not be solved because the high wind power will be at the off-peak time. Thus, there will be two ways to solve that through load shedding or DSM. But using load shedding will affect the quality of the services and customers' satisfaction level. However using the DSM will solve that issue depending upon the participation level. As clearly shown in Table 3 cell named "load with DSM", the system needs more than 10% participation level to solve the mismatch between the peak load and wind power peak. It is also clear from Fig. 6 that with the increase in the participation level the utilization percentage of wind energy increases.

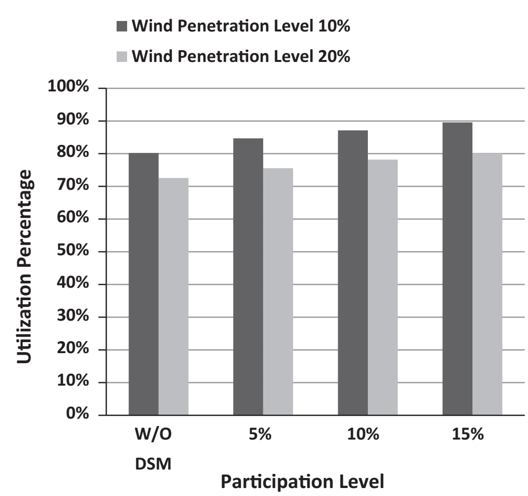

Figure 4 The percentage of utilized wind energy versus participation level in case of winter load.

Tables 4 and 5 illustrate the results of using 20% penetration level of wind energy. It is clear that the operation cost is less than the penetration level of 10%. It is obviously shown that the system still has problems regarding the mismatch between peak load and wind power peak. However it is clear

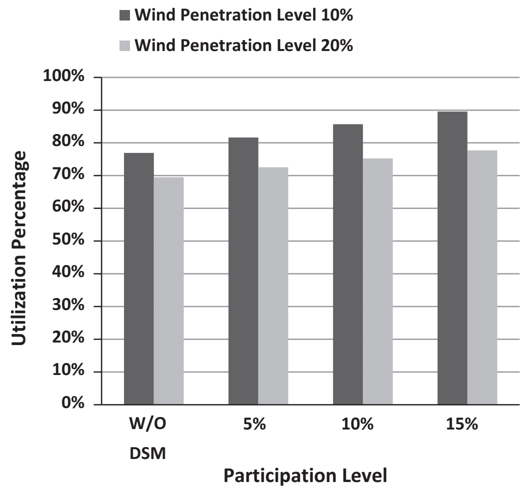

Figure 5 The percentage of utilized wind energy versus participation level in case of winter load and ramping issue in wind power.

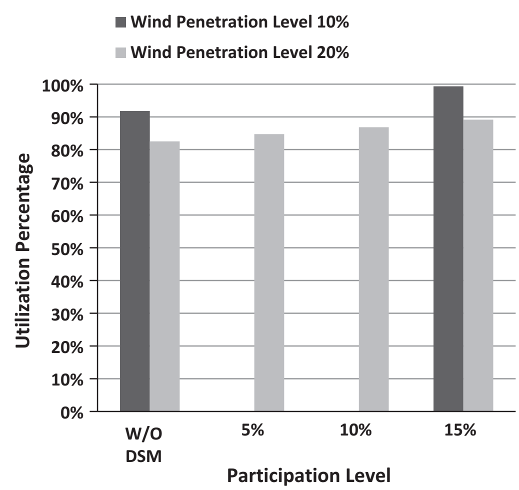

Figure 6 The percentage of utilized wind energy versus participation level in case of summer load.

that the ramping issue will be more effective when using high level of wind penetration. For example, the utilization percentage of wind energy is less than the case of no ramping issue in wind energy as shown in Figs. 4 and 5. Figs. 6 and 7 show clearly that with the increase in penetration level of wind energy, the wind energy utilization percentage will decrease but using the DSM will increase the wind energy utilization percentage.

Generally, all tabulated results ensure that the wind energy utilization percentage in the DED problem is strongly affected by the use of DSM program and in some cases it will not have solutions without using DSM because there is a great mismatch between wind and peak load as in summer case with 10% wind penetration level. Moreover, if a ramp exceeds the thermal generator allowable ramping rates in some other cases, the curtailed wind energy will be increased; however using the DSM with high penetration level can handle the issues from energy mismatch or ramping issues.

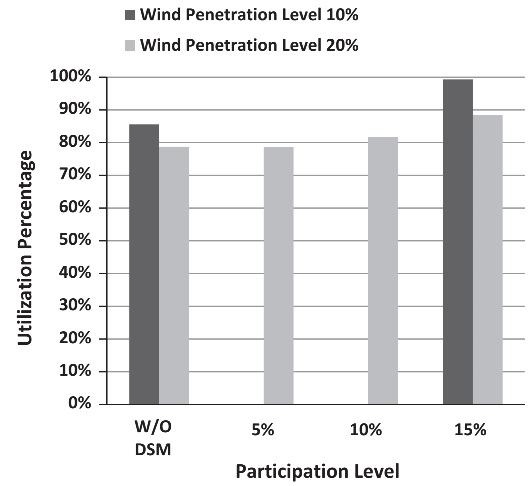

Figure 7 The percentage of utilized wind energy versus participation level in case of summer load and ramping issue in wind power.

5. Conclusions

The incorporation of high penetration of wind energy into the power system faces some difficulties such as the bad correlation between both profiles of wind energy and load, and the ramping issue. Accordingly, these problems may greatly oppose the intention of increasing the penetration of wind energy. Meanwhile, to be able to increase the penetration of wind energy, the power system needs some flexibility to accommodate this high penetration.

The incorporation of DSM through a DED problem as a flexible resource has been studied to solve the issues come from the high penetration of wind energy. Comprehensive tests have been carried out on the six generators system as a test system to verify the importance of using the DSM. Besides, the effect of different penetration levels of wind energy is extensively discussed and the results show that the ramping issue and energy mismatch have high impact when the wind penetration increases. The achieved results show that incorporating DSM will add more flexibility in the power system through shifting the shiftable loads from the peak time to the off-peak time leading to a load profile which is close to match the wind energy profile, that results in more accommodated wind energy, increased wind energy utilization percentage and great reduction in the total cost of operation.

It is worth mentioning that the different participation levels are also extensively studied for each penetration level of wind energy. The achieved results show that the good effects of increasing the participation level reduce the total cost of operation, increase the utilization percentage of wind energy and decrease the effects related to the high penetration of wind energy. The results also show that the high penetration of wind energy will decrease the operation cost.

In this paper, the DSM program targets only the residential loads, so in some cases the flexibility added to the system is not high enough to solve all the issues related to the use of wind energy, therefore incorporating the other load sectors such as industrial and commercial sectors is expected to result in more flexibility to the power system.

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The GAMS using BARON as a solver and GA with hybrid function are used for solving the DED problem for different scenarios and the results show that both of them give the same results but the GAMS is faster and does not need repetitive iterations like GA.

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