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Incorporation of Demand Response Programs and Wind Turbines in Optimal Scheduling of Smart Distribution Networks: A Case Study

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Abstract

Smart distribution networks (SDNs) plays a significant role in future power networks. Accordingly, the optimal scheduling of such networks, which include planning of consumers and production sections, inconsiderably concerned in recent research studies. In this paper, the optimal planning of energy and reserve of SDNs has been studied. Technical constraints of distribution network and power generation units are satisfied in the optimal solution of day-ahead scheduling of the network. The proposed model is studied on a case instance for evaluating the performance and analyzing the optimal solution. A modified IEEE 32-bus test system is considered as test system, in which three wind turbines and four diesel generators are placed. Industrial, residential and commercial consumers can use demand response programs to change electrical energy consuming scheduling. In this paper, incentive based demand response programs are studied for improving the optimal solution. Two demand response providers and two industrial loads are taken into account for employing demand response programs. The obtained optimal solutions are prepared and analyzed, which shows the effectiveness of the proposed model.

Keywords: DVR; Voltage sag mitigation; Tree fuzzy rule based classifier; Cuckoo search algorithm.
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Abbreviations

Indices

k	Identifier of steps of bid-quantity offers, $k = 1, 2, ..., K$
n, m	Identifier of distribution network buses, $n= 1, 2, ..., N_{Bus}$
i	Identifier of industrial loads, $i = 1, 2, ...,N_{industrial\ loads}$
d	Identifier of demand response providers, $d=1, 2, ..., N_{DRP}$
k	Identifier of steps of bid-quantity offers, $k = 1, 2, ..., K$
t	Identifier of optimization periods, $t = 1, 2, ..., 24$
j	Identifier of non-renewable DG units, j=1, 2, …, N_{DG}
w	Identifier of wind turbines, w=1, 2, …, Nw

Parameters

UR/DR	Ramp up /down rate of DG units
UT/DT	Minimum up/down time of DG units
a, b, c	Coefficients of cost functions of DG units
r, x	resistance/reactance of feeders
P_L, q_L	Active/reactive load predicted in each bus
O	Accepted load reduction of DRPs in each step
$\overline{P_{IL}}$	Upper bound of load reduction offered by industrial loads
$\overline{P_{DRP}}$	Upper bound of load reduction offered by DRPs
P_w	Wind power
P_r	Rated power
v	Wind speed
π	Offered price of DRPs in each step
v_{ci}	Cut in speed
v_{co}	Cut out speed

Functions and Variables

P_{DRP}^{DA},	Active/reactive load reduction of demand

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Q^{DA}_{DRP}	response providers
P^{DA}_{grid}, Q^{DA}_{grid}	Active /reactive power of substation
P^{DA}_{L}, Q^{DA}_{L}	Active/reactive load consumption of each bus
P^{DA}_{DG}, Q^{DA}_{DG}	Active /reactive power of DG units
P^{DA}_{W}, Q^{DA}_{W}	Active/reactive power of wind turbines
P^{DA}_{DRP}, Q^{DA}_{DRP}	Active/reactive load reduction of demand response providers
p^{E}_{g}	Power price offered to customer
R^{DA}_{IL}	Reserve capacity of industrial loads
R^{DA}_{DRP}	Reserve of demand response provider
R^{DA}_{DG}	Reserve capacity of DGs
CS_{DG}	Start-up cost of DG units
CR_{DRP}	Reserve cost of demand response providers
CE_{DRP}	Load reduction cost of demand response providers
CE_{DG}	Power generation cost of DG units
CR_{DG}	Reserve cost of DG units
CE_{IL}	Load reduction cost of industrial loads
CR_{IL}	Reserve cost of industrial loads
P^{DA}_{IL}	Active load reduction of industrial loads
R^{DA}_{DRP}	Reserve of demand response providers
l, v	auxiliary variables introduced in the AC power flow equations
u, y, z	Binary variables for DG unit commitment, start-up and shut down status
SOC	Capacity of battery
P^{f}, Q^{f}	active/reactive power flow of feeders

1. Introduction

Nowadays by expansion of power systems and increment of electrical energy consumers, the importance of distribution energy resources (DERs) and energy storage systems (ESS) are determined. Day-ahead scheduling of smart distribution networks (SDNs) has attracted researchers' attention, which includes scheduling of generation units and consuming section.

An intelligent quantum inspired evolutionary algorithm (IQEA) is implemented in [1] for obtaining the optimal solution of day-ahead scheduling of thermal generators, wind turbine (WT), photovoltaic (PV) system, and plug-in hybrid electric vehicles (PHEV). In [2], the authors aimed to minimize the fuel cost of smart network including diesel generators and WT with the consideration of time-varying characteristics of the load demand and wind power generation. In this reference, the minimization of operational cost of SDNs is done considering power losses and network constraints. Day-ahead scheduling of distribution network is studied in two-stage in [3], which considered power purchase from the market and contribution of DGs in power production in first stage. Moreover, the second stage is specified to obtain optimal dispatch of DGs and participations in power market and scheduling curtailable loads. Multi-objective day-ahead scheduling of SDN with two conflicting objectives including cost and emission minimization is studied in [4].Stochastic optimization method is applied for solve the planning problem in this reference. In [5-7], control and scheduling of DERs, including renewable generation in a MG have been studied.

Power demand increment and limitations of power generation have defined demand response (DR) programs as a practical solution for dealing with these challenges. DR programs are introduced as the capability of industrial, residential and commercial consumers to change electrical energy consuming plan. DR programs provide two main categories of programs containing incentive-based and price-based programs. In price-based programs, the price of electrical energy varies during hours of the day. As a result of [8], by employing such programs, it is expected to, decrease in costs of electricity procurement and having a flatten demand profile because of shifting demands from high price hours (peak) to low price hours. Incentive-based programs specify incentives for reducing power demand [9] .Scheduling of the industrial virtual power units, which aims to maximize profit, is studied in [10]. Price-based DR program is considered in this reference for maximizing profit. In [11], DR programs are modeled in scheduling of network taking into account spinning reserve and battery energy storage systems (BEESs). Distribution System Operator (DSO) is studied in [12] for managing power network and real time market considering residential consumers and demand response aggregators. In [13],a new framework has been used to implement DR programs in order to have more successful participation of CHP units in the power market.

In this paper, optimal energy and reserve scheduling of smart distribution network is studied. A modified IEEE 32-bus test system is considered as test instance for evaluating the performance and analyzing the obtained solutions. Incentive-based programs are considered for improving the optimal solution of day-ahead planning of the network. The obtained results are prepared and analyzed, which ensures the impact of this research study.

The remainder of this paper is organized as follows: Section II provides problem formulation. Case study is introduced in Section III. The solution method and simulation results are prepared and analyzed in Section IV. Finally, the paper is concluded in Section V.

2. Problem Formulation

This paper aims to solve day-ahead scheduling of smart distribution network. The optimization process and decisions on the behaviour of participants of the market are handled by distribution network operator (DNO). To accomplish day ahead scheduling of the network, the bids of responsive loads and forecasting data which contain wind speed, and forecasted loads are received by DNO. The required data of DG units, distribution network model and wholesale market prices are available for DNO. Distribution management system (DMS) is responsible for day-ahead scheduling. The formulation of the studied day-ahead scheduling of distribution network is provided in the following.

A) *Distribution network model*

The complex power flow equations of two buses of a radial distribution network can be stated as follows [14, 15]:

$$P_L(n) = P^f(m,n) - r(m,n)\times l(m,n) - \sum_{k\in(n,k)} P^f(n,k) \quad (1)$$

$$q_L(n) = Q^f(m,n) - x(m,n)\times l(m,n) - \sum_{k\in(n,k)} Q^f(n,k) \quad (2)$$

$$v(n) = v(m) - 2(r(m,n)\times P^f(m,n) + x(m,n) \times Q^f(m,n) + (r(m,n)^2 + x(m,n)^2)\times l(m,n) \quad (3)$$

$$l(m,n) = \frac{P^f(m,n)^2 + Q^f(m,n)^2}{v(m)} \quad (4)$$

Where,

$$l(m,n) = \left|I_{m,n}\right|^2, v(n) = |V(n)|^2 \quad (5)$$

Equations 1-3 are called branch flow equation. Such equations can be used in order to obtain the operating point of a system for a special load profile. $l(m,n)$ and $v(n)$ are auxiliary variables introduced in the AC power flow equations

B) *Wind turbine model*

The power output characteristics of wind turbine are demonstrated in Fig. 2. The available power form wind turbine considering power curve of wind turbine is formulated as follows [16]:

$$P_w(v) = \begin{cases} P_r \times \dfrac{(v - v_{ci})}{(v_r - v_{ci})} & v_{ci} \le v \le v_r \\ P_r & v_r \le v \le v_{co} \\ 0 & otherwise \end{cases} \quad (6)$$

C) *Demand response model*

In this research, incentive-based demand response programs are studied in order to improve the effectiveness of the proposed method. The consumers participated in incentive-based programs are received incentives for reducing electrical energy consumption. The studied demand response programs are modeled as the following [17]. For each demand response provider indicated by *d*, the following equality and inequality constraints are stated for modeling the step-wise bid-quantity offers of the providers. The lower and upper bounds of acceptable amount of energy reduction of demand response providers, the planned energy decrement of the providers and the related cost of reduced cost are considered as the equality and inequality constraints of the demand response providers.

$$O^d_{\min} \le o^d_1 \le O^d_1 \quad (7)$$

$$0 \le o^d_k \le (O^d_{k+1} - O^d_k)\forall k = 2,3,...,k \quad (8)$$

$$P^{DA}_{DRP}(d,t) = \sum_k o^d_k \quad (9)$$

$$CE_{DRP}(d,t) = \sum_k \pi^d_k \times o^d_k \quad (10)$$

The amount of energy reduced by a demand response provider can be utilized in planning of reserve capacity. It should be noted that for each demand response provider, the sum of energy reduced and capacity reserve should be limited by the upper bound of the maximum load decrement of the provider.

$$P^{DA}_{DRP}(d,t) + R^{DA}_{DRP}(d,t) \le \overline{P_{DRP}(d,t)} \quad (11)$$

$$CR_{DRP}(d,t) = R^{DA}_{DRP}(d,t) \times KR_{DRP}(d,t) \quad (12)$$

For modeling the participation of the industrial loads in planning of energy decrement and reserve capacity, the following equations can be stated:

$$P^{DA}_{IL}(i,t) + R^{DA}_{IL}(i,t) \le \overline{P_{IL}(i,t)} \quad (13)$$

$$CE_{IL}(i,t) = P^{DA}_{IL}(i,t) \times KE_{IL}(i,t) \quad (14)$$

$$CR_{IL}(i,t) = P_{IL}^{R}(i,t) \times KR_{IL}(i,t) \quad (15)$$

D) *Objective Function*

All the costs are considered in the objective function containing the wholesale market energy purchase, total costs of DG units, load reduction cost, reserve cost. Total costs of DG units include start-up (SU) cost, fuel cost, and reserve cost. The objective function of the proposed study is to minimize the cost of smart distribution network (SDN). The objective function of day-ahead scheduling of DMS system can be stated as follows:

$$Min \sum_{t=1}^{N_T} \begin{bmatrix} P_{grid}^{DA}(t) \times p_g^E(t) \\ + \sum_{j=1}^{N_{DG}} \begin{Bmatrix} CE_{DG}(j,t) + CS_{DG}(J,T) \\ + CR_{DG}(j,t) \end{Bmatrix} \\ + \sum_{i=1}^{N_{IL}} \{CE_{IL}(i,t) + CR_{IL}(i,t)\} \\ + \sum_{d=1}^{N_{DRP}} \{CE_{DRP}(d,t) + CR_{DRP}(d,t)\} \end{bmatrix} \quad (16)$$

In which, the first term is the cost of purchasing energy form the market. Total cost of DG unit is the second term in the above formulation. Third and fourth terms are the respective load reduction cost and reserve cost.

E) *Constraints*

Day-ahead scheduling of SDNs should be solved taking into account a series of equality and inequality constraints, which are prepared in the following.

F) *Power flow equations*

Power flow equations show that the active and reactive powers are satisfied in all of the buses of the network. The balance of active and reactive power should be taken into consideration for *n*th bus at time *t*, which can be formulated as follows:

$$\begin{aligned} &P_L^{DA}(n,t) - \sum_{j\in n} P_{DG}^{DA}(j,t) - \sum_{w\in n} P_W^{DA}(w,t) \\ &-\sum_{b\in n} (\eta^d \times P_{Bd}^{DA}(b,t) - \eta^c \times P_{Bc}^{DA}(b,t)) \\ &-\sum_{i\in n} P_{IL}^{DA}(i,t) - \sum_{d\in n} P_{DRP}^{DA}(d,t) = \\ &P^f(n,m,t) - r(n,m) \times l(n,m,t); \forall m,n,t \end{aligned} \quad (17)$$

$$\begin{aligned} &Q_L^{DA}(n,t) - \sum_{j\in n} Q_{DG}^{DA}(j,t) - \sum_{w\in n} Q_W^{DA}(w,t) \\ &-\sum_{b\in n} (\eta^d \times Q_{Bd}^{DA}(b,t) - \eta^c \times Q_{Bc}^{DA}(b,t)) \\ &-\sum_{i\in n} Q_{IL}^{DA}(i,t) - \sum_{d\in n} Q_{DRP}^{DA}(d,t) = \\ &Q^f(n,m,t) - x(n,m) \times l(n,m,t); \forall m,n,t \end{aligned} \quad (18)$$

$$\begin{aligned} &v(n,t) = v(m,t) - 2 \times (r(m,n) \times P^f(m,n,t) \\ &+ x(m,n) \times Q^f(m,n,t)) \\ &+ (r(m,n)^2 + x(m,n)^2) \times l(m,n,t) \end{aligned} \quad (19)$$

$$l(m,n,t) = \frac{P^f(m,n,t)^2 + Q^f(m,n,t)^2}{v(m,t)} \quad (20)$$

For applying a linear programming method, equation 9 can be improved to linear format taking into account v (m, t) equal to 1. So, the quadratic active and reactive power transfer formulation between buses can be revised to linear format by utilizing piecewise linear approximation concept [18].

G) *Distribution network constraints*

Technical constraints of distribution network should be considered for warranting safe operation of the network. Voltage level for all buses of the network and feeder current limits should be guaranteed.

$$\underline{V(n)}^2 \le v(n,t) \le \overline{V(n)}^2 \qquad \forall n,t \quad (21)$$

$$l(m,n,t) \le \overline{l(m,n)}^2 \qquad \forall m,n,t \quad (22)$$

$$\begin{aligned} &v(m,n,t)\ cons\tan t \\ &n = substaion\ bus \end{aligned} \qquad \forall t \quad (23)$$

$$\begin{aligned} &l(m,n,t) \le \overline{I_{sub}}^2\ m = 1 \\ &n = substaion\ bus \end{aligned} \qquad \forall t \quad (24)$$

H) *DG unit constraints*

The operational cost of a conventional power generation unit can be considered as a quadratic function of generated power. The following equation defines the operation cost of the conventional power unit:

$$\begin{aligned} &CE_{DG}(j,t) = a_j \times u(j,t) \\ &+ b_j \times P_{DG}^{DA}(j,t) + C_j \times P_{DG}^{DA^2}(j,t) \end{aligned} \qquad \forall j,t \quad (25)$$

The startup (SU) cost of conventional power units can be stated as follows:

$$\begin{aligned} &CS_{DG}(j,t) = \\ &SUC(j) \times (u(j,t) - u(j,t-1)) \end{aligned} \qquad \forall j,t \quad (26)$$

$$CS_{DG}(j,t) \ge 0 \qquad \forall j,t \quad (27)$$

The reserve cost of the conventional power unit can be assumed as a percent of the highest marginal cost of the power production of the unit. This percent is defined as KR_{DG}. So that, the following equation can be written for reserve cost:

$$\begin{aligned} &CR_{DG}(j,t) = KR_{DG} \\ &\times (b_j + 2 \times c_j \times \overline{P_{DG}(j,t)} \times R_{DG}^{DA}(j,t) \end{aligned} \qquad \forall j,t \quad (28)$$

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The lower and upper bounds of power generation of the conventional unit should be considered in solving the problem, which can be stated as:

$$\underline{P_{DG}}(j)\times u(j,t)\le P_{DG}^{DA}(j,t) \le \overline{P_{DG}}(j)\times u(j,t) \quad \forall j,t \qquad (29)$$

$$P_{DG}^{DA}(j,t)+R_{DG}^{DA}(j,t)\le \overline{P_{DG}(j)}\times u(j,t) \quad \forall j,t \qquad (30)$$

The conventional power unit should be in shut-down condition for specified hours before starting up. Moreover, the unit should produce power for determined hours before shutting-down. The inequality cost can be considered as:

$$P_{DG}^{DA}(j,t)-P_{DG}^{DA}(j,t-1)\le UR(j) \times(1-y(j,t))+\underline{P_{DG}}(j)\times y(j,t) \quad \forall j,t \qquad (31)$$

$$P_{DG}^{DA}(j,t-1)-P_{DG}^{DA}(j,t)\le DR(j) \times(1-z(j,t))+\underline{P_{DG}}(j)\times z(j,t) \quad \forall j,t \qquad (32)$$

The ramp up and down ratio of the DG power units should be taken into account, which can be stated as:

$$\sum_{h=t}^{t+UT(j)-1} u(j,h)\ge UT(j)\times y(j,t) \quad \forall j,t \qquad (33)$$

$$\sum_{h=t}^{t+DT(j)-1} (1-u(j,h))\ge DT(j)\times z(j,t) \quad \forall j,t \qquad (34)$$

For defining the startup and shut-down condition of the unit, the following equations are written:

$$y(j,t)-z(j,t)=u(j,t)-u(j,t-1) \quad \forall j,t \qquad (35)$$

$$y(j,t)+z(j,t)\le 1 \quad \forall j,t \qquad (36)$$

I) *Real-time operation constraints*

The wind generation and load demand are predicted in this research study. However, for conducting real time operation of the system, deviations from the predicted values are considered.

The scheduled reserve of conventional power generation units and responsive loads are taken into account in order to compensate the real time power shortage. The real time dispatching adjustment is limited as follows:

$$\underline{P_{DG}}(j)\times u(j,t)\le P_{DG}^{RT}(j,t) \le \overline{P_{DG}}(j)\times u(j,t) \quad \forall j,t \qquad (37)$$

$$0\le P_{DG}^{RT}(j,t)\le P_{DG}^{DA}(j,t)+R_{DG}^{DA}(j,t) \quad \forall j,t \qquad (38)$$

$$0\le P_{DG}^{RT}(j,t)\le P_{DG}^{DA}(j,t)+R_{DG}^{DA}(j,t) \quad \forall j,t \qquad (39)$$

$$0\le P_{DG}^{RT}(j,t)\le P_{DG}^{DA}(j,t)+R_{DG}^{DA}(j,t) \quad \forall j,t \qquad (40)$$

$$0\le P_{DRP}^{RT}(d,t)\le P_{DRP}^{DA}(d,t)+R_{DRP}^{DA}(d,t) \quad \forall j,t \qquad (41)$$

3. Case Study

This paper studied a modified IEEE 32-bus test system in order to evaluate the performance and ensure the effectiveness of the proposed model. According to the provided results in [19], distribution generators are connected to the appropriate buses. The studied case study is demonstrated in Fig. 1.

Three wind turbines are utilized in the test case, which are connected to buses 13, 15, and 30. The wind turbine data are adopted from [20]. The rated power of the wind turbines is equal to 3 MW. The respective cut-in and cut-out speeds of the wind turbines are selected as 3 m/s and 25 m/s. Rated speed of the wind turbines are equal to 13 m/s. The predicted speed is illustrated in Fig. 2.

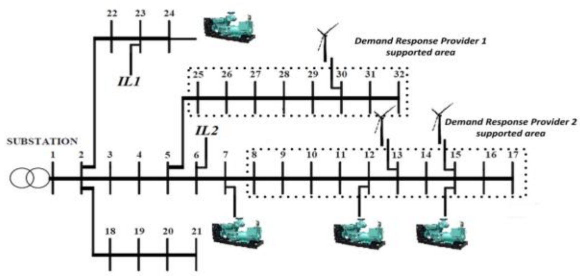

Fig.1 A modified IEEE 32-bus test system

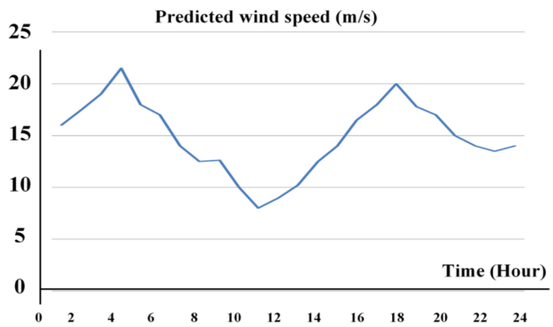

Fig.2 The predicted wind speed

Four DGs are used in the case study, which are connected to buses 7, 12, 15, and 24. The cost function coefficients of DGs are tabulated in Table 1. Data of DGs are adopted from [21].

The technical data of DGs including start-up cost (SUC), minimum up time (MUP), minimum down time (MDT), ramp up (RU) and ramp down (RD) ratio, upper and lower bounds of power production are provided in Table 2.

Table.1.
Cost coefficient of DG units

Unit	a_i (\$)	b_i (\$/MWh)	c_i (\$/MWh^2)
DG1	27	87	0.0025
DG2	25	87	0.0035
DG3	28	92	0.0035
DG4	26	81	0.184

Table.2.
Technical data of DG units

Unit	SUT ($)	MUT/MDT (h)	RU/ RD (MW/h)	Pmax (MW)	Pmin (MW)
DG1	15	2	1.8	3.5	1
DG2	25	1	1.5	3	0.75
DG3	28	1	1.5	3	0.75
DG4	26	2	1.8	4.1	1

The power market prices for 24-hour time intervals are demonstrated in Fig. 3. As it is obvious, the highest price of the market is equal to 198 $/MWh, which is related to 16th and 17th interval. Additionally, network power demand is depicted in Fig. 4.

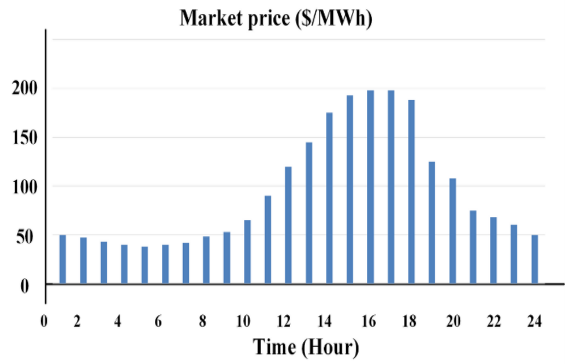

Fig.3 Market price in the scheduling time interval

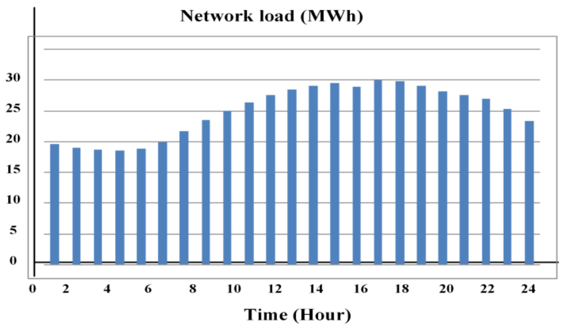

Fig.4 Network load in the scheduling time interval

4. The solution method and simulation results

A) *The solution method*

The general algebraic modeling system (GAMS) software is utilized for solving the day-ahead scheduling of modified IEEE 32-bus network with the consideration of demand response program [22]. The proposed model for obtaining the optimal solution of energy and reserve planning of the networks is a mixed integer linear programming (MILP). The objective function is minimization of the cost of reserve and energy in test instance. The solver utilized in GAMS environment is CPLEX [23]. It should be noted that the problem formulation is as MILP for ensuring that obtained solution is the global optimal solution. The employment of the proposed optimization method for solving the problem is done on a Pentium-IV, 2.8 GHz and 4GB RAM system.

B) *Simulation results*

The modified IEEE 32-bus test system which is demonstrated in Fig. 1, is simulated in this research study.

The generated powers of DG units are demonstrated in Fig.5. As seen in this figure, the DG units do not produce power between t=1 h to t=8 h. Taking into account high cost of power market from t=9 h, it is expected that the DG units will generate power. In t=9 h, DG4 started to generate power. Presence of all of the DG units in power production between t=10 h to t=22 h is obvious in this figure.

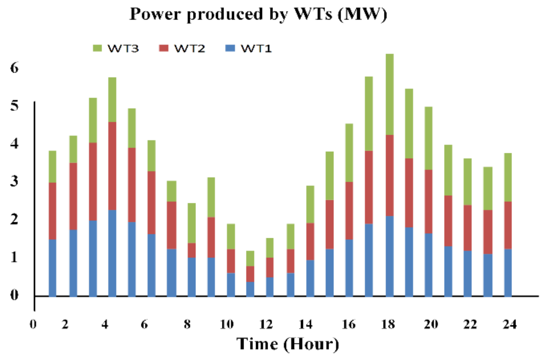

Fig.5 Power generated by WTs during scheduled time interval

Figure 6 shows the generated power by using three WTs. As seen in this figure, the maximum amount of generated power is related to t=18 h, in which the produced power is equal to 6.3 MW. The minimum produced power of WTs is related to t=11 h, in which the wind speed is in the lowest amount according to Fig. 2.

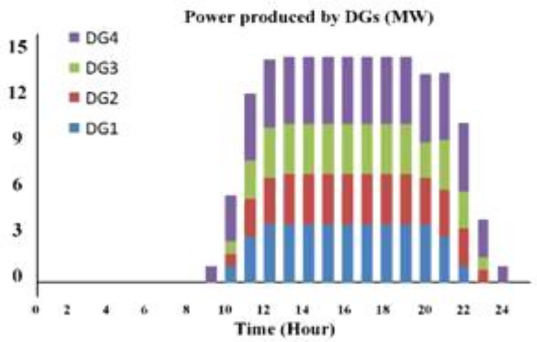

Fig.6 Power generated by DGs during scheduled time interval

The power purchased from the market is provided in Fig. 7. Considering the high price of power market between t= 11 h to t=21 h, the optimal solution is producing power by utilization of DG units. The maximum amount of power purchased from market is specified to t= 9 h, in which 20.456 MW power is bought form power market.

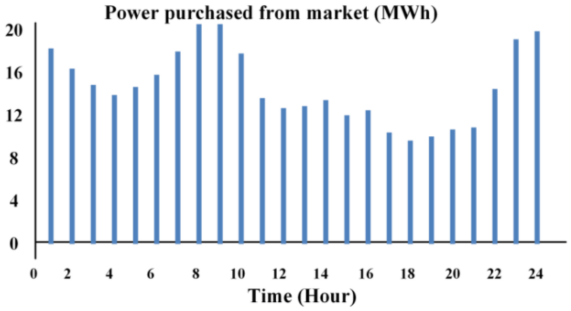

Fig.7 Power purchased from market during scheduled time interval

As noted before, an important contribution of this paper is modeling demand response program in solving day-ahead planning of distribution networks. In this research study, impact of incentive based demand response program is analyzed. In Fig. 8, accepted reduction of industrial loads is illustrated. Increment of load from t=11 h on the one hand and increasing power price of market on the other hand result to load decrement of industrial loads. As it is obvious form Fig. 8, Industrial load 2 is participated in demand response program form t=10 h to t=23 h, continuously. Moreover, industrial load 2 decreased its consuming demand in high market price hours.

Accepted reduction in reserve market of industrial loads and demand response providers and participation of |DG units in reserve market are shown in Fig. 9. As seen in this figure, demand response provider 1 has the significant role in reserve market. This provider has taken part at providing reserve power by decreasing its demand from t= 12 h to t=19 h.

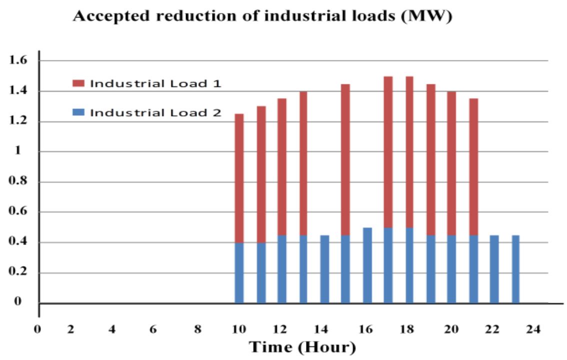

Fig.8 Accepted reduction of industrial loads

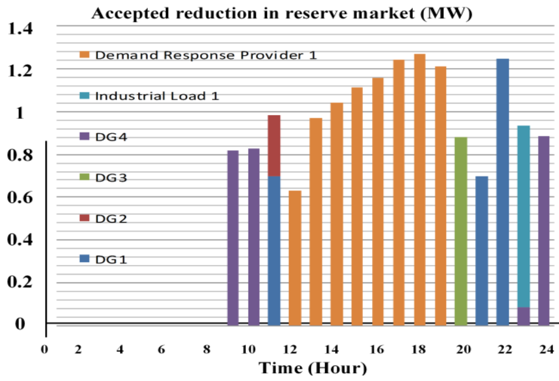

Fig.9 Accepted reduction in reserve market

5. Conclusion

Optimal scheduling of energy and reserve in smart distribution systems has been attracted researchers' attention recently. In this paper, the effect of demand response programs is analyzed in day-ahead scheduling of the network. Incentive-based programs are studied for the optimal solution of the problem. A modified IEEE 32-nus test instance is considered as a case study for proving the effectiveness of the proposed model. The network operator is able to participate in wholesale market moreover than preparing required reserve by demand response providers and industrial loads. The provided results show that the purchased power from market in high priced hours is decreased and the network is utilized distributed generators. The obtained results ensures that the proposed method is capable of obtaining the optimal scheduling of energy and reserve in distribution networks.

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