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Optimal Planning for Participating Virtual Power Plant in the Electricity Market Environment

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Abstract: Today, the virtual power plant concept has received considerable attention by researchers. A virtual power plant is a set of distributed generations, controllable loads and energy storage systems that are managed in an integrated manner by a central control system. In this study, a new model for participating of a virtual power plant in the day-ahead electricity market is proposed. The aim of proposed planning is to maximize/minimize the virtual power plant's profit/cost. In this regard, the uncertainties in loads as well as the generation of wind and solar energy units are modeled well. It has been assumed that the virtual power plant is connected to a microgrid in the downstream and to a high-voltage grid in the upstream. The proposed method is simulated on a standard IEEE 33-bus system for two strategies. In the first strategy, planning is performed without considering uncertainty of parameters. In the second strategy, model outputs are determined considering uncertainty in generation of the wind unit, generation of the solar unit and the load. Analysis and comparison of the results indicate the effectiveness of the proposed method.

Key words: Virtual power plant, electricity market, uncertainty, wind and solar generator, microgrids, power generation economics

INTRODUCTION

Now a days, distributed energy sources have become very attractive. Normally, distributed generations cannot directly participate in the electricity market. This is because of the low capacity and the stochastic nature of some of these sources such as wind and solar units. Thus, to solve the challenges of distributed energy sources such as the limitation of participating in competitive markets, their periodic nature and separate operation, they need to be managed by a central control and management system in an integrated manner. This problem may be solved using the Virtual Power Plant (VPP) concept which distributed energy sources turn into a single set. In this way, these units will be permitted to participate in the electricity market (Pudjianto *et al*., 2007; Braun and Strauss, 2008; Bakari and Kling, 2010; Mashhour and Tafreshi, 2011; Saboori *et al*., 2011).

Virtual power plant owners tend to sell their extra generation in the grid and purchase the required extra power from the main grid during the hours when their generation is insufficient. As a result, the direction of the power in the distribution grid is constantly changing in different hours of the day. Power exchange between distributed generations and consumer loads should be somehow managed (Khan *et al*., 2011).

As can be seen in Fig. 1, a virtual power plant is a set of distributed generations, controllable loads and energy storage systems that are managed in an integrated manner by a central control system (Saboori *et al*., 2011).

In the present study, a model of virtual power plant planning for participating in the electricity market using the definition of technical virtual power plant is proposed. The aforesaid planning aims to maximize/minimize the profits/costs. Simulation was performed on a standard IEEE 33-bus grid for two strategies according to scenarios. In the first strategy, planning is performed without considering uncertainty of parameters. In the second strategy, model outputs are determined considering uncertainty in generation of the wind unit, generation of the solar unit and the load.

Literature review: A market-based virtual power plant model was proposed allowing individual DER units to gain access to the electricity market by You *et al.* (2009). Asmus (2010), microgrid and virtual power plant concepts

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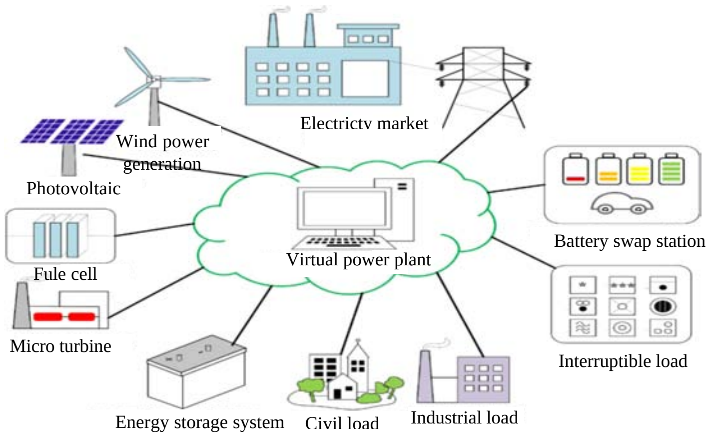

Fig. 1: Green overview of a virtual power plant

were compared introducing virtual power plant as a bridge leading to the market. Peik *et al*. (2013), the decision making problem of the virtual power plant was investigated in the short-term and mid-term market. Peik *et al*. (2013), optimal bidding of the virtual power plant and distribution grid constraints were simultaneously studied to participate in the day-ahead market. Mashhour and Moghaddas the performance of the transmission and distribution systems of the virtual power plant was examined. In this regard, the observability, controllability and the integration effect of distributed generation units for the virtual power plant operator are evaluated.

Saboori *et al*. (2011), different types of virtual power plants were investigated in technical and economic categories. Dabbagh and Eslami (2016), the design aspects of a virtual power plant were studied. Dabbagh and Eslami (2016), a new model for a VPP trading in a joint energy and spinning reserve market is proposed, using a two-stage stochastic programming approach. Zhao *et al*. (2016) the control and bidding problem of VPPs considering renewable distributed generators is investigated. Reference (Nezamabadi and Nazar, 2016), presents an arbitrage strategy for virtual power plants by participating in energy and spinning reserve and reactive power markets.

Technical virtual power plant: A technical virtual power plant comprises distributed generations within a specific geographical location. Any technical virtual power plant is characterized by the features of its distributed generation source units that are presented in an integrated manner. In other words, the geographical location of the sources in the distribution grid and their technical effects in grid utilization are taken into

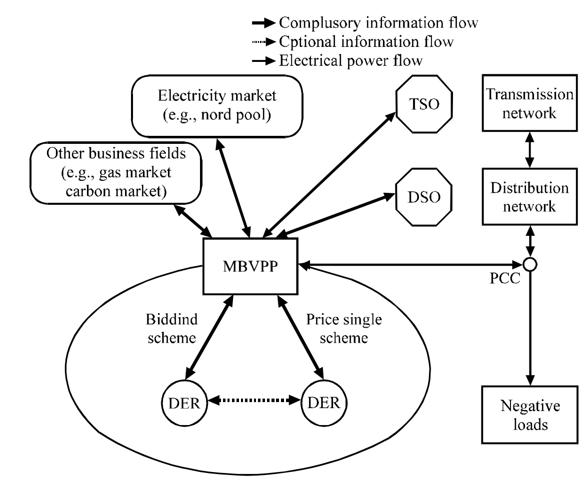

Fig. 2: Market-based virtual power plant (You *et al*., 2009)

consideration in the features of a technical virtual power plant. The performance of a technical virtual power plant involves the management of the local system for the utilization of the distribution network along with providing additional services and establishing power balance. Thus, the distribution grid operator can perform this task. By detecting the energy sources connected to the distribution grid for the system operator, the technical virtual power plant allows distributed generation units and loads to participate in the system operation (Saboori *et al*., 2011).

Market-based virtual power plant: A market-based virtual power plant aims to present a generic solution for all types of distributed generation source units to access the present electricity market. Figure 2 shows the structure of a market-based virtual power plant (You *et al*., 2009). In general, market-based virtual power plants are active in three areas, namely internal market, electricity market and ancillary service market.

MATERIALS AND METHODS

Scenario production (wind, solar and load): Renewable energy resources such as wind and solar units have a fluctuating and stochastic nature. To model uncertainties, a great number of stochastic samples is produced and utilized. In doing so, using normal distribution function and Monte Carlo technique and information data in 12000 different scenarios were produced for each parameter in every hour of day. Then, to increase the speed and precision of the solutions, the number of scenarios is reduced to 30 with the help of scenario reduction. The reduced scenarios which considered for wind power, solar power as well as the load curve are demonstrated in Fig. 3-5. In what follows, the proposed objective function for utilizing the virtual power plant as well as the constraints of the optimization problem are presented.

The proposed objective function: The proposed objective function minimizes expected cost and maximizes the expected profit as Eq. 1:

$$EC = \sum_{t\in\Gamma^T}\begin{bmatrix} \sum_{t\in\Gamma^T}\sum_{K_g\in\Gamma^K} C^{GP}_{iK_gt}p^{GP}_{iK_gt} + \sum_{t\in\Gamma^T} C^{GQ}_{it}q^{G}_{it} + \\ C^{BuHV}_t\eta^{HV}_t - R^{SeHV}_t\theta^{HV}_t \\ C^{BuMG}_t\eta^{MG}_t - R^{SeMG}_t\theta^{MG}_t - \sum_{j\in\Gamma^L} R^{L}_{jt}p^{GK}_{jt} \end{bmatrix} +$$

$$\sum_{t\in\Gamma^T}\begin{bmatrix} \sum_s \pi_s\left(\sum_{i\in\Gamma^T}\sum_{K_g\in\Gamma^K} C^{GP}_{iK_gt}p^{GP}_{iK_gts} + \sum_{i\in\Gamma^T} C^{GQ}_{it}q^{G}_{its}\right) + \\ C^{BuHV}_t\eta^{HV}_{ts} - R^{SeHV}_t\theta^{HV}_t + +C^{BuMG}_{ts}\eta^{MG}_{ts} - R^{SeMG}_t\theta^{MG}_{ts} - \\ \sum_{t\in\Gamma^L} R^{L}_{jt}p^{GK}_{jts} + \sum_{j\in\Gamma^L} C^{LoL}_{jt}p^{LoL}_{jts} + \sum_{w\in\Gamma^W} C^{W}_{wt}p^{W}_{wts} + \sum_{f\in\Gamma^F} C^{F}_{it}p^{F}_{fts} \end{bmatrix} \quad (1)$$

Constraints of the problem

First part of constraints: Equation 2, active power balance constraint:

$$\sum_{i\in\Gamma^G_n} p^G_{it} + \sum_{j\in\Gamma^L_n} p^L_{jt} + \sum_{l\in\Gamma^{in}_n} p^B_{lt} - \sum_{l\in\Gamma^{out}_n} p^B_{lt} = 0,\ \forall t, \forall s, \forall n \quad (2)$$

Equation 3, reactive power balance constraint:

$$\sum_{i\in\Gamma^G_n} q^G_{its} - \sum_{j\in\Gamma^L_n} q^L_{jts} + \sum_{l\in\Gamma^{in}_n} q^B_{its} - \sum_{l\in\Gamma^{out}_n} q^B_{lts} = 0,\ \forall t, \forall s, \forall n \quad (3)$$

Equation 4 and 5 load distribution constraints (Wang *et al*., 2015):

$$V_{nt} = \frac{V_{mt} - \left(R_L \sum_{l\in\Gamma^{in}_n\cap\Gamma^{in}_m} p^B_{lt} + X_L R_L \sum_{l\in\Gamma^{out}_n\cap\Gamma^{out}_m} q^B_{lt}\right)}{V_1}\ \forall t, \forall n \quad (4)$$

$$V^{min}_n \le V_{nt} \le V^{max}_n,\ \forall t, \forall n \quad n = m \quad (5)$$

Equation 6 and 7 constraints of power passing through lines:

$$p^B_{lt} \ge -\left(\frac{P^B_{lk_b+1} - P^B_{lk_b}}{Q^B_{lk_b+1} - Q^B_{lk_b}}\right)\left(q^B_{lt} - Q^B_{lt}\right) - P^B_{lk_b},\ \forall t, \forall i \quad (6)$$

$$p^B_{lt} \le +\left(\frac{P^B_{lk_b+1} - P^B_{lk_b}}{Q^B_{lk_b+1} - Q^B_{lk_b}}\right)\left(q^B_{lt} - Q^B_{lt_b}\right) - P^B_{lk_b},\ \forall t, \forall i \quad (7)$$

Equation 8 constraint of power balance with the main grid:

$$\eta^{HV}_t - \theta^{HV}_t + \sum_{i\in\Gamma^{in}_n} p^B_{lt} - \sum_{i\in\Gamma^{out}_n} p^B_{lt} - \sum_{i\in\Gamma^L_n} p^L_{jt} = 0,\ \forall t, \forall s, \forall n \quad (8)$$

Equation 9 constraint of maximum power purchased from the main grid:

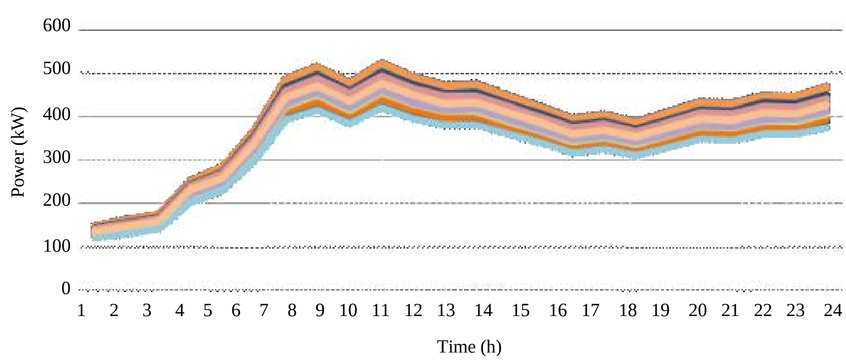

Fig. 3: Scienarios considered for wind power

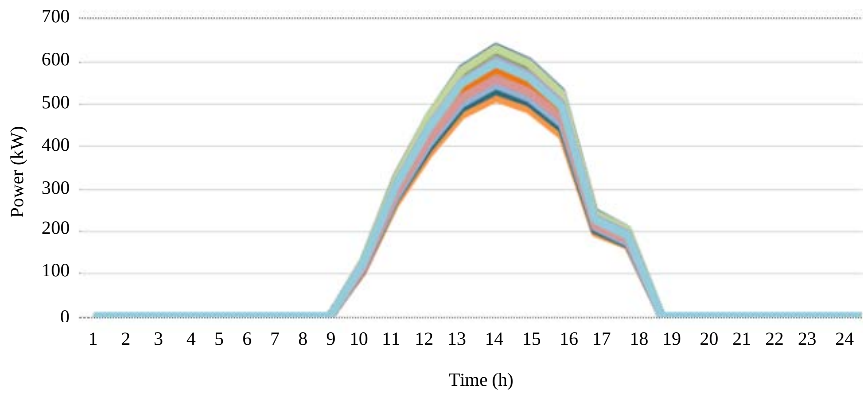

Fig. 4: Scienarios considered for solar power

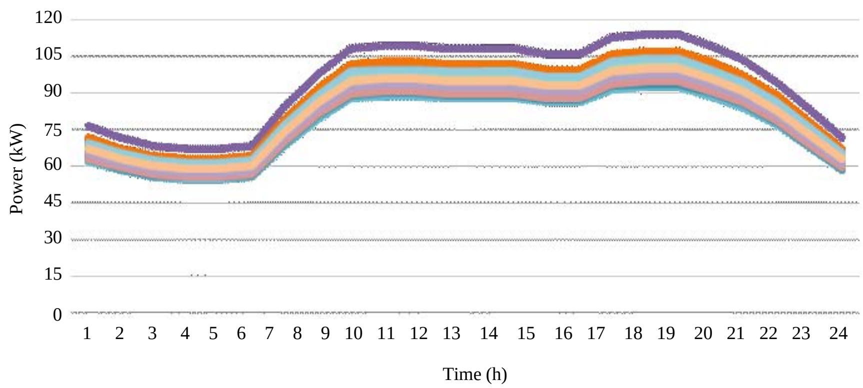

Fig. 5: Scienarios considered for solarload curve

$$0 \le \eta_t^{HV} \le \eta_t^{max}, \forall t \quad (9)$$

Equation 10 constraint of maximum power sold to the main grid:

$$0 \le \theta_t^{HV} \le \theta_t^{max}, \forall t \quad (10)$$

Equation 11 and 12 constraints of maximum power generated by microturbines:

$$0 \le p_{it}^{G} \le p_i^{G\,max}, \forall t, \forall i \quad (11)$$

$$0 \le q_{it}^{G} \le q_i^{G\,max}, \forall t, \forall i \quad (12)$$

Equation 13 and 14 constraints of proposed blocks (Morales *et al*., 2009):

$$p_{lt}^{G} = \sum_{k_g \in \Gamma_i^{Gk}} p_{ik_g t}^{GK}, \ \forall t, \forall k_g, \forall i \quad (13)$$

$$0 \le p_{ik_g t}^{GK} \le p_{ik_g}^{GK}, \ \forall t, \forall k_g, \forall i \quad (14)$$

Second part of constraints: Equation 15 active power balance constraint:

$$\sum_{i \in \Gamma_n^G} p_{its}^{G} + \sum_{w \in \Gamma_n^w} p_{wts}^{W} + \sum_{f \in \Gamma_n^f} p_{fts}^{F} - \sum_{j \in \Gamma_n^L} p_{jts}^{L} + \sum_{j \in \Gamma_n^L} p_{jts}^{LoL} + \sum_{l \in \Gamma_n^{in}} p_{lts}^{B} - \sum_{i \in \Gamma_n^{out}} p_{lts}^{B} = 0, \forall t, \forall s, \forall n \quad (15)$$

Equation 16 constraint of maximum power generated by wind units:

$$0 \le p_{wts}^{w} \le p_{wt}^{W\,max}, \forall t, \forall i, \forall w \quad (16)$$

Equation 17 constraint of maximum power generated by solar units:

$$0 \le p_{fts}^{F} \le p_{ft}^{F\,max}, \forall t, \forall i, \forall f \quad (17)$$

Equation 18 constraint of maximum load missed:

$$0 \le p_{jts}^{LoL} \le p_{jts}^{L}, \forall t, \forall s, \forall j \quad (18)$$

All other constraints are similar to the constraints of the first strategy with the subscript/superscripts (given the scenarios).

Case study: The case study in this study is a standard IEEE 33-bus system as shown in Fig. 6 (Wang *et al.*, 2015). This system is connected to a high-voltage grid in the upstream and to a microgrid in the downstream. The information of the lines and loads is found in Ghasemi and Moshtagh (2013). The characteristics of micro-turbine units, wind and solar units as well as the information of electricity purchase and sale price from and to the main grid are considered as Wang *et al.* (2015). The data of the proposed energy blocks and the data of maximum practical power generation of wind and solar units are extracted by Morales *et al.* (2009), Nezamabadi and Nazar, 2016), respectively. Figure 7 displays hourly electricity price in a day.

RESULTS AND DISCUSSION

Simulation results: The objective function proposed in section 3 was simulated on the previously introduced grid and the results were presented. To better compare the results, the simulations were conducted based on two different strategies:

First strategy: Absence of wind and solar units in the system.

Second strategy: Presence of wind and solar units in the system. The virtual power plant was expected to use its surface units at first. In case of power shortage, the plant could then make use of the units in the microgrid and ultimately, it could purchase from the main grid in case of bigger demands. It was also predicted that the profit earned from power sale in the second strategy would increases in comparison with the first strategy thanks to the entry of wind and solar units and their low cost.

Simulation results of the first strategy: In this strategy, the generation of micro-turbine units and the power exchanged with the main grid are investigated in the absence of units with uncertainty in generation. The results are shown in Fig. 8-10.

It can be seen that during off-peak hours, i.e., from 23-6, the generation of micro-turbine units is lower compared with other hours (Fig. 8) and they sell their extra generation to the main grid in addition to compensating loads (Fig. 9). During middle hours, i.e. from 7-16 and from 21-22, it can be observed that sale to the main grid gradually decreases owing to increase in loads (Fig. 9), the generation of units increases (Fig. 8) and electricity is purchased from the main grid because of power shortage (Fig. 10). During peak hours, i.e., from 17-20, purchase from the main grid is on the increase (Fig. 10) and the generation of microturbines is at a maximum (Fig. 8). (Werner and Remberg, 2008)

Simulation results of the second strategy: In this strategy, the generation of all units and the power exchanged with the main grid were examined in the presence of parameters with uncertainty. The simulation results of this section are shown in Fig. 11-14.

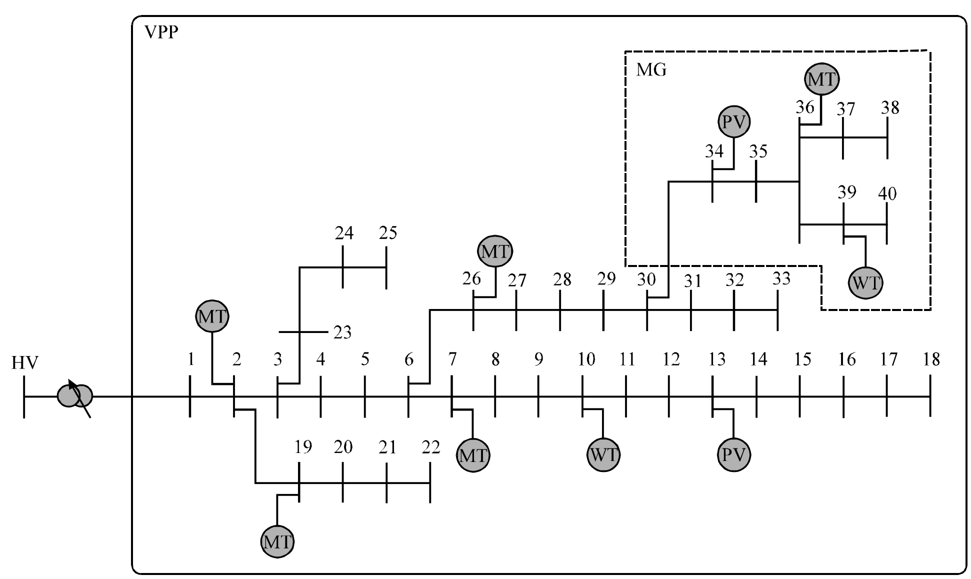

Fig. 6: Grid of the case study

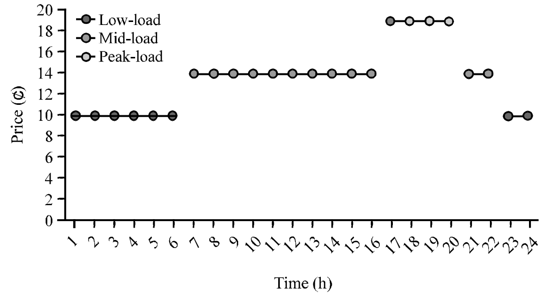

Fig. 7: The electricity price during a day

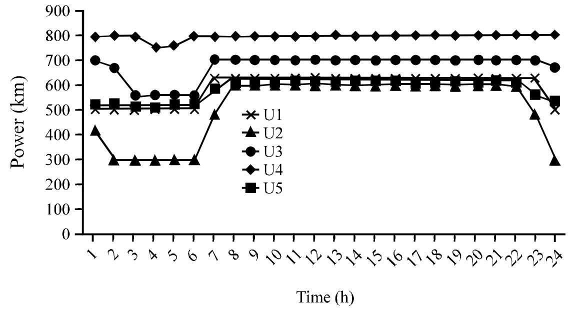

Fig. 8: Power generated by microturbine units

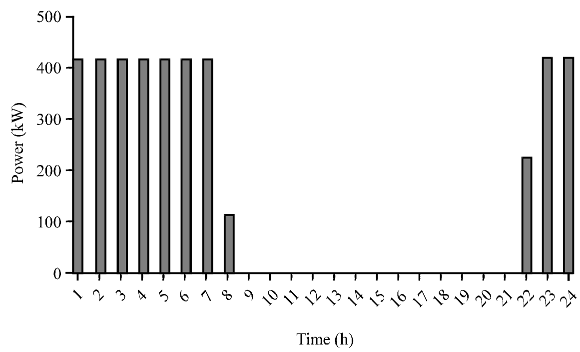

Fig. 9: Power sold to the main grid

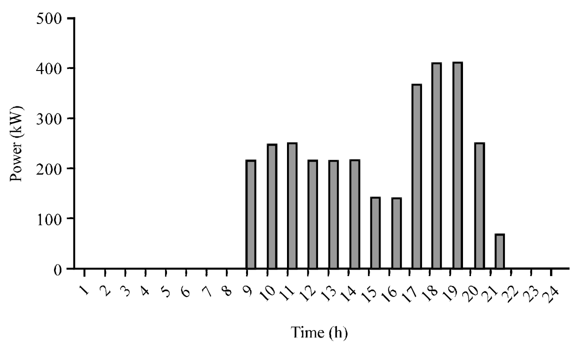

Fig. 10: Power purchased from the main grid

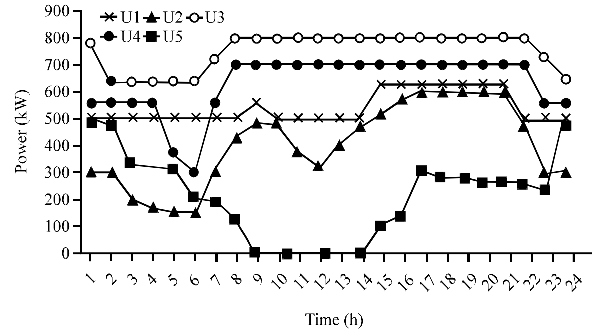

Fig. 11: Power generated by microturbine units

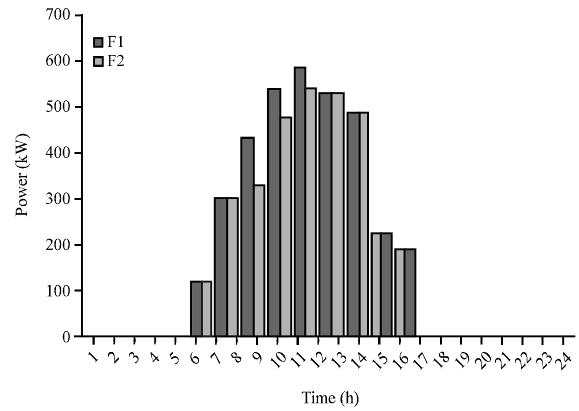

Fig. 12: Power generated by solar units

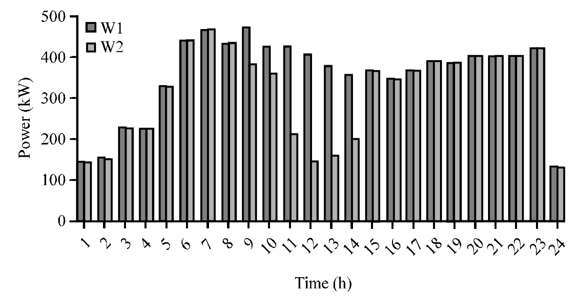

Fig. 13: Power generated by wind units

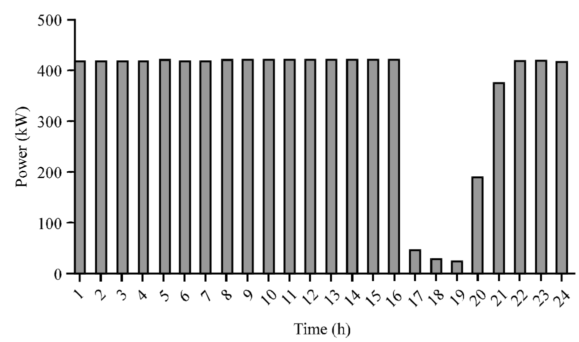

Fig. 14: Power sold to the main grid

As can be seen, during off-peak hours, the generation of the units is not at a maximum due to the low level of loads (Fig. 11). In spite of this, they sell their extra generation to the main grid to raise the profit of the virtual power plant in addition to supplying the loads (Fig. 14).

During middle hours, especially from 9-14 when the reduction is more conspicuous, what accounts for the reduced generation of micro-turbines is the existence of photovoltaic units (Fig. 12) and their low power generation cost in comparison with the micro-turbines. The fifth unit that exists in the microgrid reaches a minimum, i.e., zero from 9-14 owing to the existence of photovoltaic and wind units that contain a lower power generation cost. Since, the load existing therein is supplied by its photovoltaic and wind units, power dispatch to the virtual power plant may also be seen. During peak hours, the generation of micro-turbines rises due to increase in loads. As can be seen, the fifth unit in the microgrid has also increased its generation (Fig. 11). In middle hours, the generation of micro-turbine units is on the decrease that can be seen in Fig. 11.

The important point here is the fact that the virtual power plant makes use of wind units throughout the 24 h in the second strategy due to their existence and low cost (Fig. 13). However, it is observed in this strategy that not only is there no need to purchase from the upstream grid but also sale to the main grid is on the increase to maximize the profit throughout the 24 h due to the existence of wind and photovoltaic units (Fig. 14).

Comparison of the profits of first and second strategies: Table 1 shows the total profit earned in the proposed optimization model. In the first strategy, power generation is low owing to the absence of wind and photovoltaic units and their low utilization cost. In peak-load hours, not only does the virtual power plant not sell to the main grid, but also it has to purchase electricity from the main grid to compensate the demanded loads. This has caused the maximum profit to decrease.

In the second strategy, the power generation of the virtual power plant has risen due to the presence of wind and photovoltaic units. Not only is there no need to purchase electricity from the main grid but also the extra power generation is sold to the main grid throughout all hours in order to maximize the profit. This has resulted in increased profit.

Table 1: The total profit in first and second strategies ($)

Profit of the 1st strategy	Profit of the 2nd strategy
484670	1422180

CONCLUSION

The Virtual Power Plant (VPP) concept has recently attracted the attention of many researchers. Different units including renewable resources can be considered in VPP. Therefore, proposing an appropriate model for operation of VPP is very important. In this study, a new model for the utilization of a virtual power plant to participate in the electricity market is proposed. In the proposed model, energy resources with uncertain generation (wind and solar generators) were also taken into consideration. The simulations were performed with two strategies on a standard IEEE 33-bus system.

According to simulation results, in case the owner of all available sources including the downstream grid sources (microgrid) is the virtual power plant itself, the virtual power plant costs decrease and the profit increases as a result. The virtual power plant tries to use its own power generation sources so far as possible. Then, it makes use of the downstream grid generation when in need. In the end, it purchases power from the main grid in case of power shortage.

The virtual power plant uses their maximum practical power throughout all hours to increase its profit, due to the very low utilization cost of renewable wind and solar units. Considering two strategies and comparing their costs, it may be seen that the presence of renewable sources such as wind and solar units, considerably affects the increased profit of the virtual power plant.

NOMENCLATURE

t	=	Index of time
s	=	Index of scenario
i	=	Index of micro-turbine units
j	=	Index of loads
n	=	Index of buses
k	=	Index of proposed blocks
π_s	=	Probability of scenario s
R_t^{SeHV}/C_t^{BuHV}	=	Cost/revenue of purchasing/selling electricity from/to the main grid
R_t^{SeMG}/C_t^{BuMG}	=	Cost/revenue of purchasing/selling electricity from/to the microgrid
C_{wt}^{W}	=	Generation cost of wind power
C_{wt}^{W}	=	Generation cost of solar power
C_{it}^{GQ}	=	Reactive power cost of micro-turbine units
C_{jt}^{Lol}	=	Cost of lost load
$C_{ik_gt}^{GP}$	=	Cost of the kth proposed block
R_{jt}^{L}	=	Revenue earned from selling electricity to consumers
V_{nt}	=	Voltage of bus
P_{jts}^{LoL}	=	Amount of loads lost

$\theta^{HV}{}_t/\eta^{HV}{}_t$	=	Power purchased/sold from/to the main grid
$\theta^{MG}{}_t/\eta^{MG}{}_t$	=	Power purchased/sold from/to the microgrid
q_{it}^{G}/p_{it}^{G}	=	Active/reactive power of microturbine units
p_{wt}^{W}	=	Power of wind units
p_{ft}^{F}	=	Power of solar units
$p_{ik_g t}^{GK}$	=	Power of the kth proposed energy block
q_{jt}^{L}/p_{jt}^{L}	=	Active/reactive power of loads
q_{lt}^{B}/p_{lt}^{B}	=	Active/reactive power passing through lines
V_n^{max}/V_n^{min}	=	Minimum/maximum voltage of busbars
X_L/R_L	=	Resistance/reactance of the lines

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