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# Probabilistic planning for participation of virtual power plants in the presence of the thermal power plants in energy and reserve markets

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**Abstract.** Renewable energy-based on virtual power plants (VPPs) has recently attracted considerable attention for participating in energy and reserve markets due to the disadvantages of thermal power plants (TPPs). The present paper aims to maximize the VPP profitability in distribution networks including thermal power plants, at minimum load cost, using a mathematical model for implementing the VPP and evaluating its role in the energy and reserve markets. The proposed model includes a series of probabilistic scenarios used to consider the uncertainty of wind/solar generation. Therefore in the first step, the lower bound of the problem, i.e., minimizing demand cost for all the units, should be calculated. It determines the status of VPP units based on the best-case scenarios. Afterward, the problem is cut to calculate the upper bound of the problem which is maximizing the profit of the VPP. The problem is evaluated in two cases: one is the presence of VPP only in the energy market and the other is the simultaneous presence of the VPP in the reserve and energy markets. The computation ends with the convergence of lower and upper bounds of the problem. Since the proposed method uses a piece-wise model of thermal units and the problem has nonlinear equations, Mixed Integer Programming (MIP) used to calculate the contribution of units by utilizing GAMS software. Finally, the VPP profitability calculated for the day-ahead energy and reserve market after determining the method for the participation of power plants in supply at the minimum cost. The proposed method was then applied to a sample system consisting of three thermal plants, three wind farms, two solar farms, and two energy storage systems, considering several situations to examine the impact of the resources and also the resulting profitability in the energy and reserve market. The final step was the analysis of the results.

**Keywords.** Virtual power plant; distributed generation; energy storage; probabilistic scenario; optimization.

## 1. Introduction

Virtual power plant (VPP) is an economic, technical, and operational system that aggregates the capacities of distributed energy resources (DERs), either consuming or producing electricity, One of the main technical aspects of the virtual power plant is the diversity of energy resources, in which case there is a single power plant but consisting of various units as renewable energy resources, energy storage systems, and controllable loads.

Given the capacity of DERs such as solar cells and wind farms and their relatively unpredictable nature, it is necessary to manage the energy exchange between DERs and the network to provide the possibility of participation in the market. This is possible to achieve with the concept of the virtual power plant, through which DERs aggregated as a single system to exchange energy with the market and to provide complementary services [1, 2]. The profitability of the virtual power plant with renewable resources, intermittent loads and storage units is evaluated in [3–6]. In most cases, the profitability of the virtual power plant in the energy market was negative, while the overall profitability of the virtual power plant was positive by participating in the storage market.

To make the virtual power plant profitable, a market is presented in [7, 8] for intermittent loads. Energy storage units are utilized in [9–12] to cover the uncertainty of VPP units. Non-renewable resources operating alongside the VPP network are not considered in [13, 14] and they are referred to as the “upstream network”. In [15–19] the energy exchanges in the structure of the VPP grid have been considered and the results obtained from other adjacent units in the grid have not been investigated.

In [20–25], the simultaneous effect of energy and heat generated under the VPP is investigated. In [26–30], the presence of several renewable sources, next to the thermal

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power plant (TPP) has been investigated to reduce generation costs and environmental pollution, while the issue of the presence of a VPP next to a TPP and the exchange of energy between them has not been addressed.

In this paper, the ideaof the simultaneous operation of a virtual power plant next to a thermal power plant is investigated. Since the intermittent loads do not exist on the grid, the storage devices were used to exchange with the TPP and it was attempted to cover the uncertainties of the VPP through the TPP. As noted in most references, the simultaneous presence of renewable sources next to the TPP has been utilized to reduce the operation cost and environmental pollution. In the proposed scheme in this paper, by integrating renewable resources as a virtual power plant, its role in the energy and reserve market is examined.

## 2. Implementation of the network

The network studied in this paper consists of three thermal generation units (TGs) and five distributed generation units (DGs), including wind and solar farms. According to figure 1, where a load of Buses 4 and 7 (a total of 10 MW) are considered as VPP internal loads. Table 1 includes the DG specifications and constraints, such as production constraints, table 2 covers the ES specifications and constraints, The initial capacity of each storage unit is 20 MW. It is also assumed that all DGs are capable of reserve supply. Table 3 includes the TG specifications and constraints. Finally, table 4 presents the parameters of transmission lines. Also, figure 2 illustrated the load prediction for a 24-hour interval.

## 3. The implementation results

The proposed algorithm was applied to the sample network (figure 1) with three thermal units, two solar farms, three wind farms, and two energy storage units. It was assumed that the storage units are charged through the units TG1, TG2, and TG3, and that DG3 and DG5 are solar units, DG1, DG2, and DG4 are wind ones, and TG1, TG2, and TG3 are gas (thermal) ones. The VPP consists of five DGs participating in the energy and reserve market and two ES participating in the energy market. Furthermore, the total internal load of the virtual power plant was assumed to be 10 MW, which was considered on Buses 4, 10 and 12. The software programs GAMS used to solve the optimization problem. Several scenarios were first considered to examine the impact of renewable energy resources on operation costs. Figure 3 shows the first state for scenario 1 (S = 1) without any renewable resource, in which case the burden of supply is only carried by thermal units. The operation cost, in this case, is 287,660 monetary units. Table 5 includes the information on the share of supply by the thermal units in scenario 1. As mentioned in section 2, it is possible to model this uncertainty by generating scenarios (S=5N DG = 55 = 3125). Also, the occurrence probability of each scenario is obtained by multiplying the probabilities

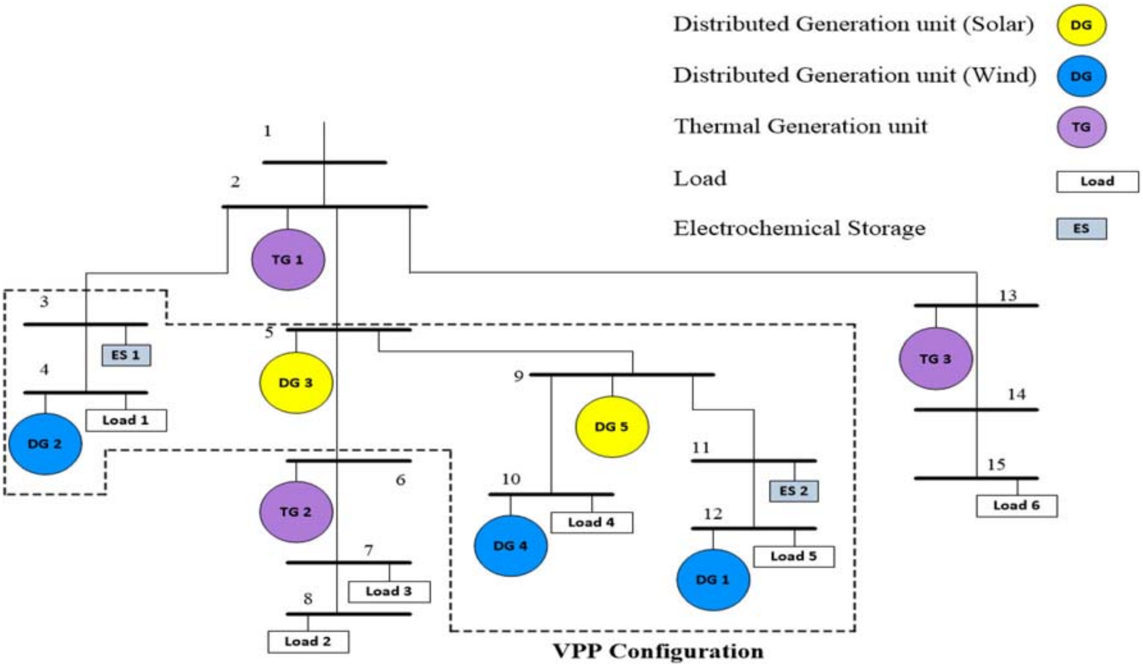

**Figure 1.** Test network.

**Table 1.** Specifications of distributed generation units.

| Units | DG1 | DG2 | DG3 | DG4 | DG5 |
|---|---|---|---|---|---|
| Pmin (MW) | 20 | 20 | 35 | 20 | 30 |
| Pmax (MW) | 85 | 75 | 115 | 90 | 110 |
| a (Monetary unit/MW$^2$h) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| b(Monetary unit/MWh) | 0.105 | 0.126 | 0.085 | 0.127 | 0.092 |
| MU (h) | – | – | 4 | – | 3 |
| MD (h) | – | – | 4 | – | 3 |

**Table 2.** Specifications of energy storage units.

| Energy storage units | ES1 | ES2 |
|---|---|---|
| Maximum capacity(MW) | 56 | 50 |
| Minimum capacity (MW) | 8 | 5 |
| Charge rate (MW/h) | 12 | 15 |
| Discharge rate (MW/h) | 12 | 15 |
| Energy conversion factor | 90% | 90% |

**Table 3.** Specifications of thermal generation units.

| Units | TG1 | TG2 | TG3 |
|---|---|---|---|
| Pmax (MW) | 455 | 130 | 130 |
| Pmin (MW) | 150 | 20 | 20 |
| a (Monetary unit/h) | 1000 | 700 | 680 |
| b (Monetary unit/MWh) | 16.19 | 16.60 | 16.90 |
| c (Monetary unit/MW$^2$h) | 0.00048 | 0.002 | 0.00211 |
| MU (h) | – | – | – |
| MD (h) | – | – | – |
| hot start cost (Monetary unit) | 4500 | 550 | 560 |
| cold start cost (Monetary unit) | 9000 | 1100 | 1120 |

**Table 4.** Transmission line parameters.

| Line | Resistance (pu) | Reactance (pu) |
|---|---|---|
| 1–2 | 0.004 | 0.025 |
| 2–3 | 0.001 | 0.03 |
| 2–5 | 0.005 | 0.05 |
| 2–13 | 0.004 | 0.025 |
| 3–4 | 0.001 | 0.03 |
| 5–6 | 0.005 | 0.05 |
| 5–9 | 0.004 | 0.025 |
| 6–7 | 0.005 | 0.03 |
| 7–8 | 0.004 | 0.025 |
| 9–10 | 0.001 | 0.03 |
| 9–11 | 0.004 | 0.025 |
| 11–12 | 0.005 | 0.05 |
| 13–13 | 0.004 | 0.025 |

related to the values of wind speed and solar radiation in that scenario.

Since the VPP profitability is calculated by minimizing the supply cost with all the DGs operating, it is not necessary to consider all the scenarios. It is thus sufficient to focus on the last scenario (s = 3125) that includes all the DGs. Table 6 and figure 4 show the status of the participation of units (TGs and DGs) in stochastic planning for scenario 3125. The cost of operation, in this case, is 198,440 monetary units. Given the fact that the DG operation cost is limited to maintenance costs, it is considered negligible. The addition of each DG not only increases the number of scenarios but also decreases the energy generated by TG units. This creates an advantage for a virtual power plant with thermal power plants in the energy market, as it would be possible to generate energy at a lower cost.

The virtual power plant still needs the TG units to generate energy for load supply. Two situations can be thus considered for VPP profitability: (1) allocating a percentage of production for reserve, (2) utilization of storage units.

According to the predicted energy price in figure 5 and table 6, the VPP profit in the energy market is equal to 40667.46 monetary units (table 7). Figure 6 shows the amount of reserve allocated by DGs in scenario 3125. Accordingly, the virtual power plant allocated its minimum production to the energy market and the rest of the reserve market to increase its profitability. A comparison between

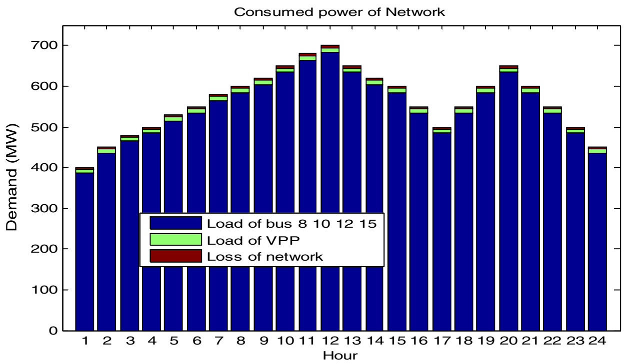

**Figure 2.** The demand load of the system.

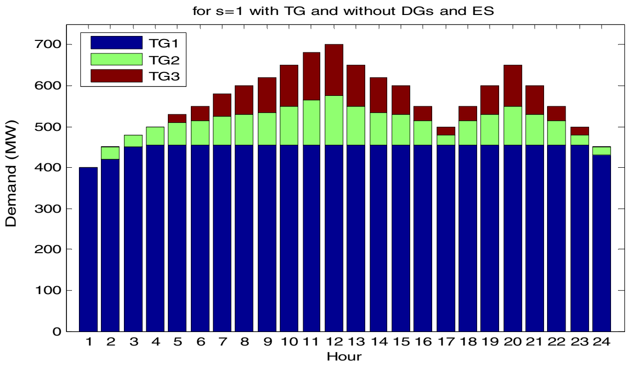

**Figure 3.** The share of supply by TG units in scenario 1.

**Table 5.** Method of participating thermal units in load supply without renewable units (MW).

| Hour | TG1 | TG2 | TG3 | Hour | TG1 | TG2 | TG3 |
|---|---|---|---|---|---|---|---|
| 1 | 400 | – | – | 13 | 455 | 95 | 100 |
| 2 | 420 | 30 | – | 14 | 455 | 80 | 85 |
| 3 | 450 | 30 | – | 15 | 455 | 75 | 70 |
| 4 | 455 | 45 | – | 16 | 455 | 60 | 35 |
| 5 | 455 | 55 | 20 | 17 | 455 | 25 | 20 |
| 6 | 455 | 60 | 35 | 18 | 455 | 60 | 35 |
| 7 | 455 | 70 | 55 | 19 | 455 | 75 | 70 |
| 8 | 455 | 75 | 70 | 20 | 455 | 95 | 100 |
| 9 | 455 | 80 | 85 | 21 | 455 | 75 | 70 |
| 10 | 455 | 95 | 100 | 22 | 455 | 60 | 35 |
| 11 | 455 | 110 | 115 | 23 | 455 | 25 | 20 |
| 12 | 455 | 120 | 125 | 24 | 430 | 20 | – |

Table 6 and figure 6 reveals that the same amount must be covered by TG units for each DG allocation. Although table 6 shows that TG1 is the only unit that seems to be operating, it made TG2 and TG3 operating as well by allocating a percentage of DG production to reserve (figures 6 and 7). In this case, the operation cost equals 252.070 monetary units.

According to figure 10, the profit will be equal to 50987.125 monetary units if the virtual power plant participates simultaneously in both the energy and reserve markets (table 8). Accordingly, the VPP profit will reach 10365.665 monetary units if a percentage of production is allocated for reserve. The results of tables 7 and 8 obtained without considering the impact of energy storage units. The operation of the storage units is as follows: they purchase energy and charge when the price is minimum, and then sell the energy to maximize the VPP profitability when the price is maximum mode (without allocating the DG production for reserve). Accordingly, ES1 and ES2 are quickly charged during those hours when the price of energy is low and discharged within those when the price of energy is high. Their charge and discharge rates are 12 and 15 MW,

**Table 6.** Method of participating units (whether TG and DG) in load supply (MW).

| Hour | TG1 | TG2 | TG3 | DG1 | DG2 | DG3 | DG4 | DG5 |
|---|---|---|---|---|---|---|---|---|
| 1 | 289 | – | – | 39 | 37 | – | 35 | – |
| 2 | 354 | – | – | 34 | 34 | – | 30 | – |
| 3 | 410 | – | – | 25 | 25 | – | 20 | – |
| 4 | 404 | – | – | 34 | 32 | – | 30 | – |
| 5 | 419 | – | – | 39 | 37 | – | 35 | – |
| 6 | 359 | – | – | 44 | 42 | 35 | 40 | 30 |
| 7 | 358 | – | – | 49 | 47 | 43 | 45 | 38 |
| 8 | 319 | – | – | 53 | 52 | 63 | 55 | 58 |
| 9 | 216 | – | – | 81 | 72 | 85 | 86 | 80 |
| 10 | 211 | – | – | 83 | 73 | 100 | 88 | 95 |
| 11 | 208 | – | – | 84 | 74 | 115 | 89 | 110 |
| 12 | 225 | – | – | 85 | 75 | 115 | 90 | 110 |
| 13 | 265 | – | – | 63 | 62 | 100 | 65 | 95 |
| 14 | 285 | – | – | 53 | 52 | 90 | 55 | 85 |
| 15 | 312 | – | – | 52 | 51 | 70 | 50 | 65 |
| 16 | 285 | – | – | 51 | 50 | 60 | 49 | 55 |
| 17 | 271 | – | – | 50 | 49 | 43 | 49 | 38 |
| 18 | 340 | – | – | 49 | 48 | 35 | 48 | 30 |
| 19 | 455 | – | – | 49 | 48 | – | 48 | – |
| 20 | 455 | 50 | – | 49 | 48 | – | 48 | – |
| 21 | 455 | – | – | 49 | 48 | – | 48 | – |
| 22 | 412 | – | – | 47 | 46 | – | 45 | – |
| 23 | 365 | – | – | 46 | 45 | – | 44 | – |
| 24 | 318 | – | – | 45 | 44 | – | 43 | – |

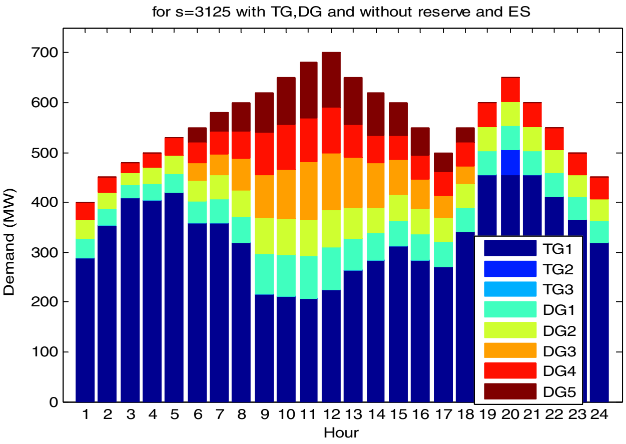

**Figure 4.** Load supply by generation units in scenario 3125.

respectively. Accordingly, ES1 and ES2 are quickly charged during those hours when the price of energy is low and discharged within those when the price of energy is high. Their charge and discharge rates are 12 and 15 MW, respectively. According to table 9 and figure 8, the storage units can operate in two modes: they act as a load and purchase energy from the thermal power plant when the price of energy is low, and they act as a producer and sell

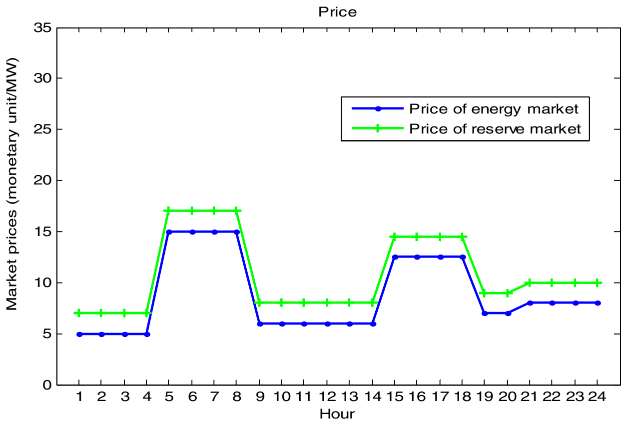

**Figure 5.** Day-ahead predicted the price of energy and reserve.

**Table 7.** Profit made by DGs participating in the energy market in scenario 3125.

| Energy Market in 24 h | |
|---|---|
| Cost of VPP Production | – 4181.6 |
| VPP Loss | – 860.94 |
| Cost of VPP Load | – 2120 |
| DG5 profit | 7690 |
| DG4 profit | 10600 |
| DG3 profit | 8345 |
| DG2 profit | 10359 |
| DG1 profit | 10836 |
| Total | 40667.46 |

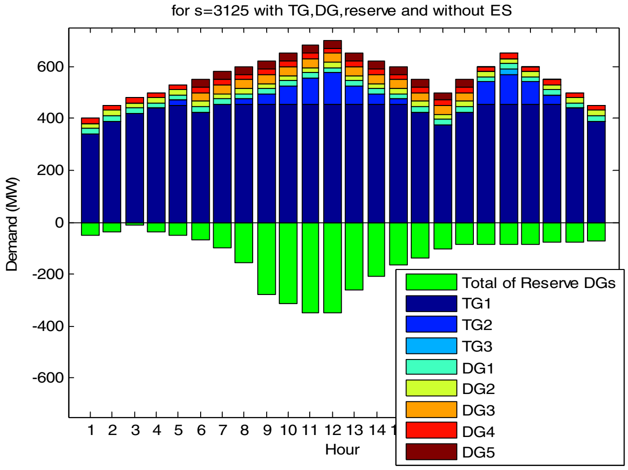

**Figure 7.** The share of generation units in supply for scenario 3125 by allocating a percentage of DG production to reserve.

the energy in the market when the price is high. This approach is similar to same-commodity arbitrage. In figure 9, the negative ES columns indicate that the storage unit is charging and receiving energy and the positive columns indicate that they are discharging and supplying energy. Conversely, the TG unit is increasing the energy generation and decreasing its energy at the same time. The cost of operation, in this case, is 198.510 monetary units. According to table 9, the VPP profit in the energy market is 42088.065 monetary units with the storage units participating. This reveals an increase of 1420.605 monetary units as compared to the case where the storage effect was not included (table 10). Figures 10, 11 and 12 illustrate the operation of storage units in the second mode (by allocating the DG production for reserve). Accordingly, the only difference is ES1 operation at midnight, when a 12 MW charge was not possible due to the TG1 limited capacity, the TG2 maximum production, and the TG3 minimum production. In this case, the operation cost equals 251.080 monetary units. The VPP profit in the energy and reserve market is 52480.93 monetary units according to table 11, indicating an increase of 1493.805 as compared to the case where the storage effect was not included (table 11).

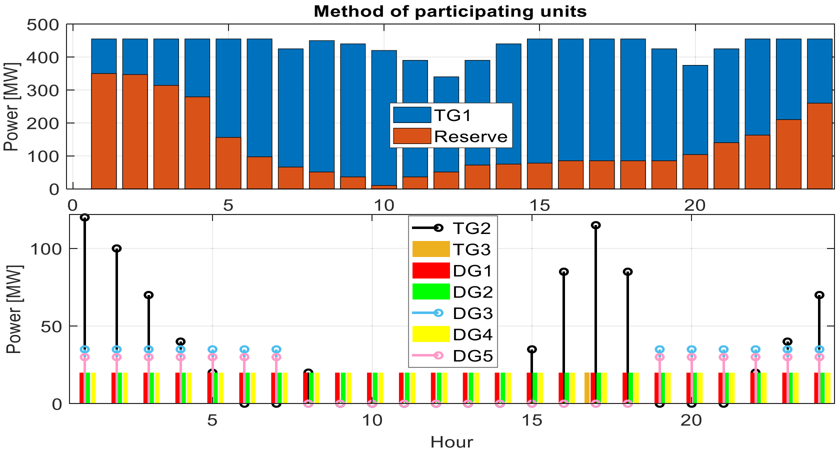

**Figure 6.** Method of participating units (whether TG and DG) in load supply by allocating a percentage of DG production to reserve (MW).

**Table 8.** Profit made by DGs participating in the energy and reserve market in scenario 3125.

| | | |
|---|---|---|
| Reserve Market in 24 h | Total reserve profit: DG1+DG2+DG3+DG4+DG5 | 33065 |
| Energy Market in 24 h | Cost of VPP Production | – 810.65 |
| | VPP Loss | – 382.23 |
| | Cost of VPP Load | – 2120 |
| | DG5 profit | 3930 |
| | DG4 profit | 4240 |
| | DG3 profit | 4585 |
| | DG2 profit | 4240 |
| | DG1 profit | 4240 |
| | Total | 50987.125 |

**Table 9.** The method for the participation of units (whether TG, DG, and ES) in supply without allocating DG production for reserve.

| | | |
|---|---|---|
| Reserve Market in 24 h | Total reserve profit: DG1+DG2+DG3+DG4+DG5 | 33065 |
| Energy Market in 24 h | Cost of VPP Production | – 810.65 |
| | VPP Loss | – 382.23 |
| | Cost of VPP Load | – 2120 |
| | DG5 profit | 3930 |
| | DG4 profit | 4240 |
| | DG3 profit | 4585 |
| | DG2 profit | 4240 |
| | DG1 profit | 4240 |
| | Total | 50987.125 |

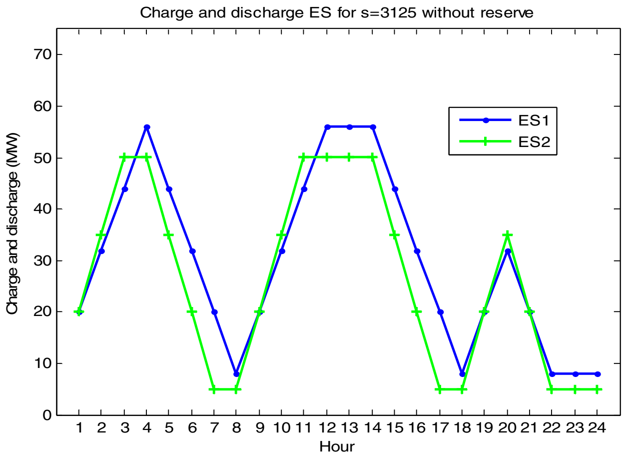

**Figure 8.** Charge and discharge of storage units without reserve.

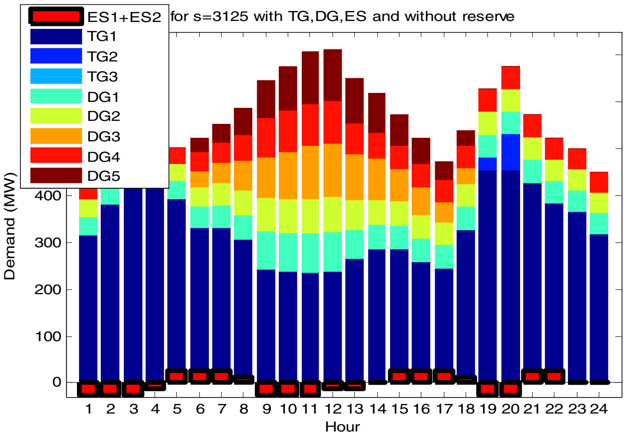

**Figure. 9.** The share of supply by TG, DG, and ES units without reserve.

**Table 10.** Profit made by DGs and ESs participating in the energy market in scenario 3125.

| Energy Market in 24 h | |
|---|---|
| Cost of VPP Production | – 4247.6 |
| VPP Loss | – 890.835 |
| ES2 profit | 772.5 |
| ES1 profit | 744 |
| Cost of VPP Load | – 2120 |
| DG5 profit | 7690 |
| DG4 profit | 10600 |
| DG3 profit | 8345 |
| DG2 profit | 10359 |
| DG1 profit | 10836 |
| Total | 42088.065 |

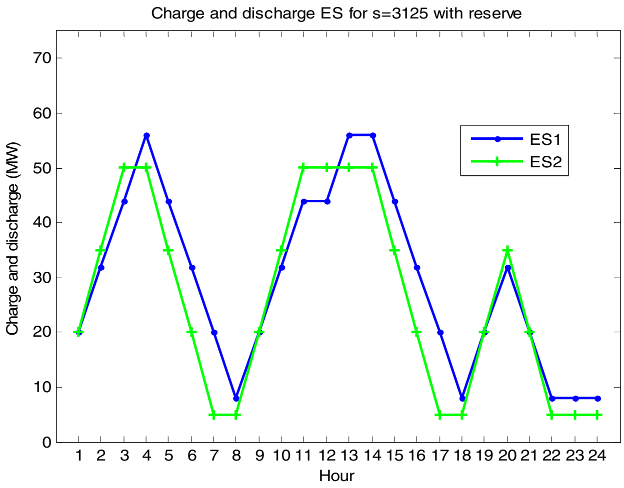

**Figure 10.** Charge and discharge of storage units with reserve.

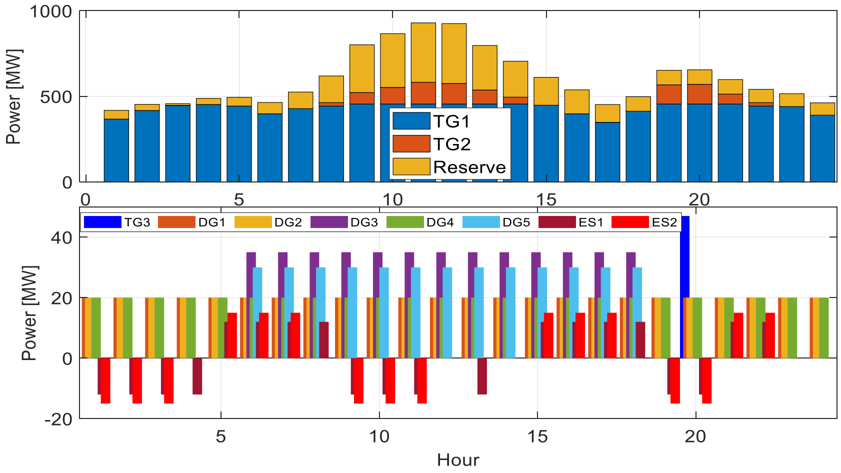

**Figure 11.** The method for the participation of units (whether TG, DG, and ES) in supply with allocating DG production for reserve (MW).

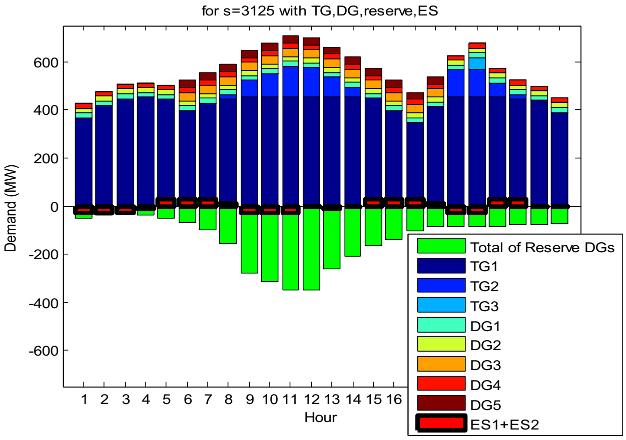

**Figure 12.** The share of supply by TG, DG, ES units with reserve.

**Table 11.** Profit made by DGs and ESs participating in the energy and reserve market in scenario 3125.

| | | |
|---|---|---|
| Reserve Market in 24 h | Total reserve profit: DG1+DG2+DG3+DG4+DG5 | 33065 |
| Energy Market in 24 h | Cost of VPP Production | – 876.65 |
| | VPP Loss | – 412.13 |
| | ES2 profit | 772.5 |
| | ES1 profit | 816 |
| | Cost of VPP Load | – 2120 |
| | DG5 profit | 3930 |
| | DG4 profit | 4240 |
| | DG3 profit | 4585 |
| | DG2 profit | 4240 |
| | DG1 profit | 4240 |
| | Total | 52480.93 |

## 4. Conclusion

The first step in the present research project was the calculation of the operation cost of the system under the influence of renewable resources, controlled by a virtual power plant with thermal units. Then, a set of probabilistic scenarios were taken into consideration for simulating the wind speed and radiation uncertainties to solve the participation problem. In the next step, a mathematical model was developed for solving the VPP profitability sub-problem in the day-ahead energy and reserve market, considering all the system constraints such as those of distributed generation units, charging and discharging status of storage units, and the network itself.

The large number of distributed generation units in the grid leads to different scenarios for the virtual power plant. The first is to minimize the generation cost so that the best-case scenarios can be extracted. The next factor is the similar issue of Bender's decomposition, which results in two situations: the presence of a virtual power plant in the energy market or the simultaneous presence in the energy and reserve market. The next factor is cutting off the problem, which is similar to Bender's decomposition and results in two situations: the presence of a virtual power plant in the energy market or the simultaneous presence in the energy and reserve market. Due to the presence of storage units, the problem of participation of the VPP has been studied in various cases and due to nonlinear equations and high volume of computations, MIP has been used to solve the problem.

The simulation results clearly showed that the VPP participation provides higher profitability in the reserve market than the energy market. All of this depends on the presence of the TPP to support the uncertainty of the VPP.

However, the performance of the virtual power plant is such that in most cases the usage of the power plant is minimum and only one thermal generator is in use. It was also found that it is possible to achieve higher profitability with storage units in the energy market, by purchasing energy from thermal units during the hours when the market energy price is low and selling it within those when the market price increases. The results thus prove that a virtual power plant could play an influential role in the energy and reserve markets.

Steps in the present research project was the calculation of the operation cost of the system under the influence of renewable resources, controlled by a virtual power plant with thermal units. Then,a set of probabilistic scenarios were taken into consideration for simulating the wind speed and radiation uncertainties to solve the participation problem. In the next step, a mathematical model was developed for solving the VPP profitability sub-problem in the day-ahead energy and reserve market, considering all the system constraints such as those of distributed generation units, charging and discharging status of storage units.

Features of the proposed method can be described as follows:

- There is a combination of renewable energy sources such as solar cells and wind turbines in the VPP that generate energy in 24 h.
- Comparing the virtual and thermal power plants in discussing the energy and reserve market.
- Using TPP to offset VPP uncertainty and energy exchange between storage and thermal units to increase profits in the energy market. Allocation of the minimum energy generation of the VPP in the energy market and it’s surplus in the reserve market to increase profit in the reserve market.
- Provide a mathematical model for the participation of virtual and thermal power plants with minimum generation cost, so that three thermal units are used more than one of them. This has raised both customer satisfaction and profitability of the virtual power plant by reducing generation costs.
- Scenario reduction by considering two factors, one is to minimize generation costs and the other to cut the problem, which reduces the overall evaluation of scenarios and the volume of computations.
- Non-interruption of virtual power plant load.
- Improve Bender’s decomposition by taking into account the generation cost constraint, which is applicable when the TPP operates with the VPP. Otherwise, it would not be feasible in the presence of units with lower generation costs.

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