Hybrid Stochastic Risk-Based Approach for a Microgrid Participating in Coupled Active and Reactive Power Market

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Abstract

In recent years, simultaneous participation in energy and ancillary services (AS) markets has been very profitable for microgrids (MG). High penetration of renewable energy sources (RES) in energy supply, due to the uncertainties of these products, increases the need for AS. Also, active and reactive powers are completely related, so in this paper the microgrid simultaneous participation in the active and reactive power and ancillary services (regulation up and regulation down, spinning reserve and non-spinning reserve) markets is modeled considering uncertainty of wind and solar generations. The relation between active and reactive power generation of each generator is calculated based on capability diagrams and mathematical equations. Conditional value at risk (CVaR) is used for risk management, and probability of calling ancillary services is calculated. Uncertainties of wind and solar generations are modeled using their probability distribution functions (PDFs). The ERCOT market simulation is discussed to calculate the participation of each unit in all the mentioned markets based on real-world data.

Keywords**:** Ancillary services, Non-spinning reserve, Optimal bidding, Reactive power market, Regulation up, Regulation down, Spinning reserve

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Nomenclature

Acronyms

CVaR	Conditional Value at Risk
DER	Distributed energy resources
DG	Distributed generation
EM	Energy market
AS	Ancillary services
MT	Micro turbine
ESS	Energy storage system
MG	Microgrid
PV	Photovoltaic system
RES	Renewable energy sources
WT	Wind turbine
PDF	Probability distribution function

Parameter

A	Annuitization coefficient (dimensionless)
G	Operating & maintenance costs, per unit generated energy ($/kW)
μ	Average of beta distribution
σ	Standard deviation of beta distribution
E_{pvr}	Standard power generation of PV unite
r_{std}	Standard solar irradiation level W/ m2
p_{wr}	Standard power generation of wind unit
λ	Probability of calling ancillary services
r	Solar radiation
V	Wind speed
v_{in}	Cut-in wind speed
v_r	Rated wind speed
v_{out}	Run-out wind speed
$\pi(s)$	Probability of each scenario
δ	Confidence level
W	Risk-aversion parameter
UR	Ramp up rate
DR	Ramp down rate
P^{max}	Maximum generation power
P^{min}	Minimum generation power

η^{st}	Charging efficiency
ζ^{st}	Discharging efficiency
$P_{st}^{dsh\,\max}$	Maximum discharge in one hour
$P_{st}^{sh\,\max}$	Maximum charge in one hour

Variables

R	Revenue
γ	Price
$O\gamma$	Offer price
S	Apparent power
P	Active power
Q	Reactive power
C	Cost function
var	Value at risk
η_s	Auxiliary variable for calculating CVaR
$P_{st}^{sh/dsh}$	Charging/discharging power of storage
$s_{sh/dsh}$	Charging/ discharging state of storage
X_s	Reactance of synchronous machine-based DG
I_t	Steady state armature current
V_t	Voltage at terminal bus of a DG

Indices

s	Index of scenario
q	Index of reactive power
E	Index of energy
rd	Index of regulation down
ru	Index of regulation up
sp	Index of spinning reserve
sn	Index of non-spinning reserve
as	Index of ancillary services
asg	Index of ancillary services generation
std	Index of standard
ave	Index of average
req	Index of requirement
dch	Index of discharge storage
ch	Index of charge storage
n	Index of set of generating units

1. Introduction

1.1. Background

In a deregulated power system, the transmission system operator maintains the security and reliability of the power system. In recent decades, with the restructuring of the power system and the expansion of distributed and renewable generations (for reasons such as, air pollution, reduced consumption of fossil fuels, ...) with possible problems in the electrical network (power plant failure, losses of transmission lines, forecasted changes in load consumption ...) may have destructive effects on the performance of the transmission system operator and security and stability of power system [1,2]. To improve power system performance, the independent system operator needs AS [3]. AS are some essential services to maintain the reliability and stability of the system [4,5]. In this study voltage control, frequency control, spinning reserve and non-spinning reserve are noticed. Also this paper has considered coupled active and reactive market. The incentive for developing integrated systems is to realize gains from tight coordination in daily operations, while strengthening system reliability [6]. One of the most important reasons for controlling reactive power is blackouts in the power systems (September 28, 2003 in Italy, September 23, 2003 in Sweden and Denmark) [5]. These AS are usually offered in separate markets and in a competitive economic environment.

MG includes generators of electrical energy (renewable generators, micro turbines (MT), etc.), electrical loads and sometimes energy storage system (ESS) [7], which can be a consumer or supplier of electricity with the coordination of its members [8]. MGs can maximize their profits by participating in AS markets while selling electrical energy. Participation in AS markets reduces the capacity to participate in the energy market (EM), as well as reactive power generation, reduces active power generation. Therefore, in order to optimally plan a MG for simultaneous participation in all of these markets, the exact cost and revenue of participation in each market must be studied. MGs generally operate on a small scale in the electrical grid, and their bid has almost no effect on the market. Therefore, a MG can offer the optimal participation amount per hour for each market to achieve the maximum possible profit, by carefully considering the cost and revenue of each market, the parameters affecting the amount of electrical energy production (wind speed, solar radiation ...), energy and AS prices and technical constraints.

1.2. Literature review

Various articles have discussed the optimal planning of simultaneous participation in the energy and AS markets. In some articles, participation in the reactive power market has also been considered. The first papers proposed the values of the parameters to be definite and predicted, and then papers considered uncertainties. In [2], multi-stage stochastic programming model used for optimal planning of virtual power plants (VPP) in day-ahead energy and secondary reserve market considering the uncertainty of wind speed and clearing price. In [7], a decision-making model is presented to determine the optimal participation in the Day-Ahead EM. In this paper, the uncertainty of the solar generator and also the participation in the supply of thermal energy is modeled. In [9], an equilibrium bi-level model is proposed to find the best MG planning of buy or sell energy in day-ahead market (DAM). In [10], the proposed robust bidding model for participation in the active and reactive power market with considering large number of distributed energy resources (DER), and additional losses of reactive power generation in the DAM is described. In [11], the constraints and equations of reactive power generation in synchronous generators and their cost are expressed based on the capability curve. This article is one of the earliest studies on this subject.

Reference [12] expressed participation of flexible ramping products (wind turbine (WT), photovoltaic system (PV), MT and ESS) in the joint energy and AS markets. Uncertainties of renewable generation and market prices are model with hybrid stochastic/robust model. Authors of [13] express the comprehensive MINLP model for optimal planning of renewable low voltage MG in the day-ahead joint energy and reserves market. The uncertainty of energy price is modeled using lognormal PDF. In [14], optimal planning for smart distribution networks with the aim of minimizing the cost of active and reactive power and reducing CO2 pollution, are presented using information gap decision theory method. Uncertainties of wind generation, energy price and load consumption are modeled for this purpose.

In [15], an active and reactive power market sequential planning model (reactive power bids are submitting after the end of the active power market) for different DER. The effect of reactive power generation on active power reduction is modeled using the capability curves and also considers the amount of CO2 pollution in the objective function. In [16] an arbitrage model for simultaneous participation in the active power, reactive power and reserve market for VPPs is modeled according to the constraints of the system to maximize VPPs profits by considering the capacitor bank.

In [17], optimal market participation planning is proposed by considering the uncertainty of renewable products (WT and PV), outage of generation units and demand response program and CVaR method is used for risk management. In [18], the decision-making problem for the simultaneous participation of MG in the energy and reserve market using a two-level framework is presented. Uncertainty of wind speed, solar radiation, probability of calling reserve, energy and reserve prices are modeled using related PDFs and CVaR is used for risk management. In [19] optimal planning to minimize the cost of participation in energy and AS markets (including reactive power) for each unit and upstream grid is discussed. Stochastic programming technique used to model uncertainties. Authors of [20] considered a stochastic objective function in the coupled active and reactive power market with considering the amount of air pollution and demand response programs. Wind generation and load consumption are modeled using Weibull and Gaussian PDFs.

1.3. Contributions

Previous studies have examined MG's participation in the active and reactive power and AS markets. Uncertainties of renewable generating units, probability of call AS and different type of AS, with considering additional loss of production reactive power are not present in any of the studies at the same time.

In this paper, a novel objective function for joint active and reactive power market and various AS (regulation up and regulation down, spinning reserve and non-spinning reserve) is proposed for the first time. Also this paper introduces a new model of participation in the spinning reserve and non-spinning reserve markets at the same time.

1.4. Paper organization

The rest of the paper is organized as follows: Section 2 describes the problem, introducing different types of AS and voltage controllers, modeling the cost of active and reactive power production, objective function and constraints, uncertainties and risk management. Section 3 provides a case study with real-world data for ERCOT market and finally Section 4 is conclusion.

2. Problem description and mathematical modeling

2.1. Market modeling

In previous systems, generators only participated in the EM. Now the MG (Fig. 1) can achieve the maximum possible profit with optimal planning simultaneous participation in the energy and AS markets. Due to the intermittent and fluctuating nature of wind power and solar radiation, a system operator is forced to provide AS to ensure the adequate reliability of the power system [21]. In this study voltage control, frequency control, spinning reserve and non-spinning reserve are discussed. For this planning, all the effective factors in this planning must be carefully studied.

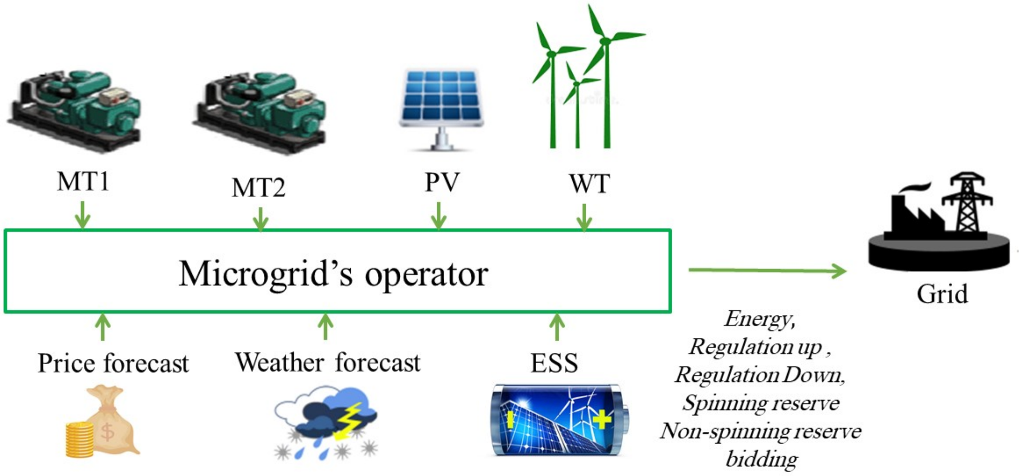

Fig. 1. The MG test system.

2.2. Ancillary services

AS are some essential services to maintain the reliability and stability of the system [4,5]. Voltage control, frequency control, spinning reserve and non-spinning reserve are discussed in this paper.

2.2.1. Voltage control

The voltage of system must always be within the limited range to prevent blackouts and destructive effects on the power system. Voltage can control by increase or decrease of reactive power. Capacitor banks or synchronous condensers, SVCs (Static VAR compensators), STATCOMs can use to fulfill the need for reactive power in normal condition but they are slow for abnormal conditions. In abnormal conditions sufficient reactive power must be generated or absorbed to maintain voltages in the right amount [12]. MG can produce this reactive power for voltage control [4].

2.2.2. Regulation

Frequency deviation from the limited range causes the fault of protection relays, shutdown of generators, etc. Therefore, it must always be set within the allowable limit. To compensate small deviations, generators increase or decrease their output in a short period of time (less than a few seconds). In some markets only one type of frequency control is offered, but in some markets, regulation up (increasing output power) and regulation down (decreasing output power) AS are offered separately [22].

2.2.3. Spinning reserves

In case of problems such as power plants or transmission lines failure or unexpected increase in energy consumption, generators increase their output. Generators generally have 10-15 minutes to increase power. Generators that are online but do not work at full capacity can provide this service [22].

2.2.4. Non-spinning reserves

To help the power system to cope with undesirable events and failures, non-spinning reserves is provided in 10 to 30 minutes. This service can be provided by units that are offline but can increase their output at the requested time [22].

2.3. Revenue of ancillary services

The profit of participation in AS has two parts: the profit from the AS contract and the profit from call AS [23,24]. The revenue from AS contracts expressed in Eq. (1) (regardless the usage of reserve capacity in the actual operation period).

$$\mathrm{R}_{as} = P_{as}.\gamma_{as} \tag{1}$$

If the power system needs AS, the cost of power generation must be paid separately to the production units. Reserve generation benefit can be expressed as:

$$R_{asg} = P_{asg}.\gamma_{asg} - c_{asg} \tag{2}$$

2.4. Cost function of generators

2.4.1. Cost function of micro turbine

These micro turbine's cost curves are represented as cubic or quadratic functions and piecewise linear functions. MTs use a quadratic fuel cost function such as the fuel cost curve [25,26]:

$$C_{MT} = b_1 \times P^2 + b_2 \times P + b_3 \tag{3}$$

Fig. 2 illustrates the relation between the active and reactive power of synchronous generators [5,11,15].

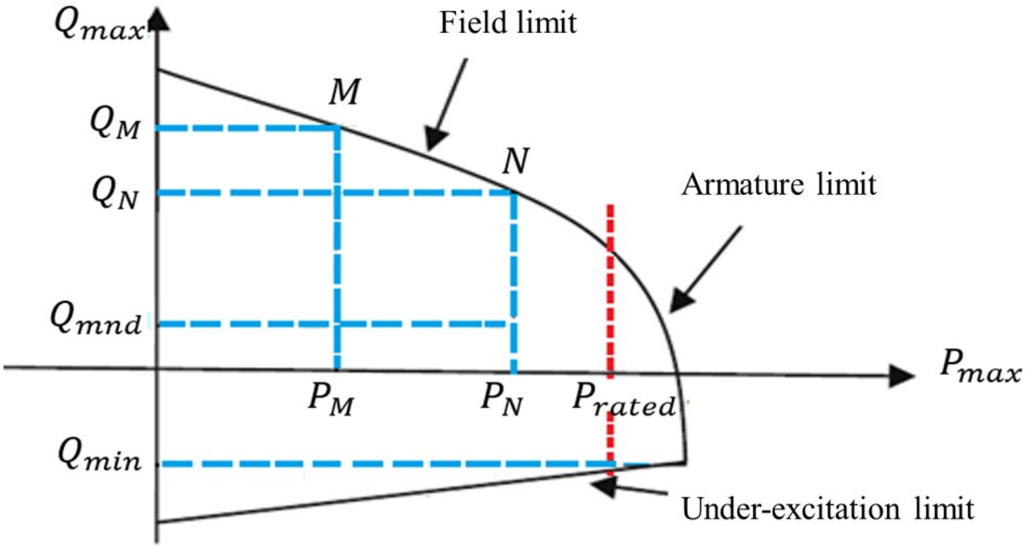

Fig. 2. Synchronous generator capability curve

Q_{mnd} is some of reactive power is generated by the synchronous generators to meet its own needs, including in boiler pump motors, water circulation pump motors, fan motors, etc… In P_N the reactive power can change between Q_{mnd} and Q_N without change in active power but it will increase the active power losses in winding [5,11].

In this section to produce reactive power, generator does not reduce its active power, so only the cost of availability is paid to the generator. Any increase of the reactive power provided by a generator from Q_N, reduces the active power and increases the active power losses. The producer expects this reduction to be paid for [5,11].

$$\text{expected payment function (EPF)} = \gamma_0 + \int_{Q_{min}}^{0} \gamma_1 dQ_{MT} + \int_{Q_{mnd}}^{Q_N} \gamma_2 dQ_{MT} + \int_{Q_N}^{Q_M} \gamma_3 dQ_{MT} \quad (4)$$

γ_0 is the availability price, γ_1 is the cost of loss price offer for operating in under excited mode ($Q_{min} to$ 0), γ_2 is the cost of loss price offer for operating in region ($Q_{mnd} to$ Q_N) and γ_3 is the opportunity price offer for operating in ($Q_N to$ Q_M). Eq.(5) and (6) models the synchronous generator's capability curve [11].

Capability curve limit (Armature current limit)

$$Q_{MT\leq} \sqrt{(V_t\, I_t) - P_{MT}^2} \quad (5)$$

Capability curve limit (Field current limit)

$$Q_{MT\leq} \frac{-V_t^2}{X_s} + \sqrt{\left(\frac{E^{max} V_t}{X_s}\right)^2 + P_{MT}^2} \quad (6)$$

Fig. 3 presents the relationship between active and reactive power production and the amount of additional active power losses of synchronous generators [27]. Active power loss in Fig. 3 can estimate by Eq. (7) and (8) in each point or in each region and generally provided by the generator's manufacturer [27]. For example, in R1, for every KVAR of reactive power, the active power loss can be equal to 5 watts.

$$\Delta s = S' - S = \sqrt{Q^2 + P^2} \;\; - P_{max}^2 \quad (7)$$

$$\frac{\Delta s}{Q} = \frac{\sqrt{Q^2+P^2} \; - P_{max}^2}{Q} \quad (8)$$

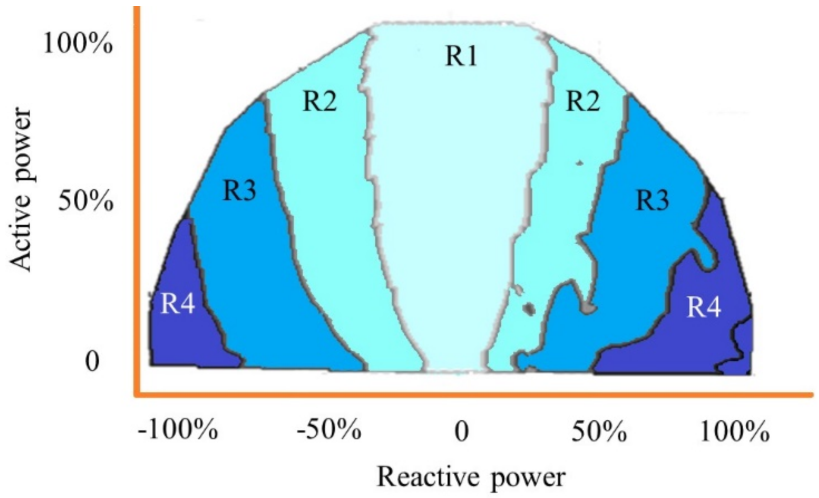

Fig. 3. Synchronous generator additional loss by production reactive power

2.4.2. Cost function of wind turbine

The cost function of wind generation includes the costs of operation and maintenance (O&M) (the initial investment costs and land costs of the power plant has no effect on MG's bidding) [28].

$$C_{WT} = G_{WT} \times S \tag{9}$$

With the development of power electronics and the ability to control WT, the use of these generators has expanded rapidly. These converters have the ability to control the active and reactive power of WT. A typical wind turbine and its converter is illustrated in Fig. 4 [20].

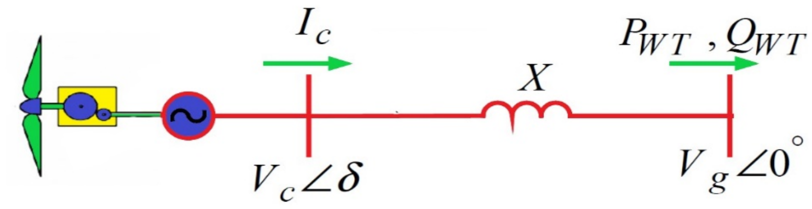

Fig. 4. Typical model of a WT

This system can control the amount of active and reactive power. Increasing reactive power generation reduces active power generation as well as active power losses (copper losses and magnetization losses). Therefore, the cost of this reduction must be paid to the WT. Fig. 5 shows the relationship between active and reactive power generation in a wind generator [15,20].

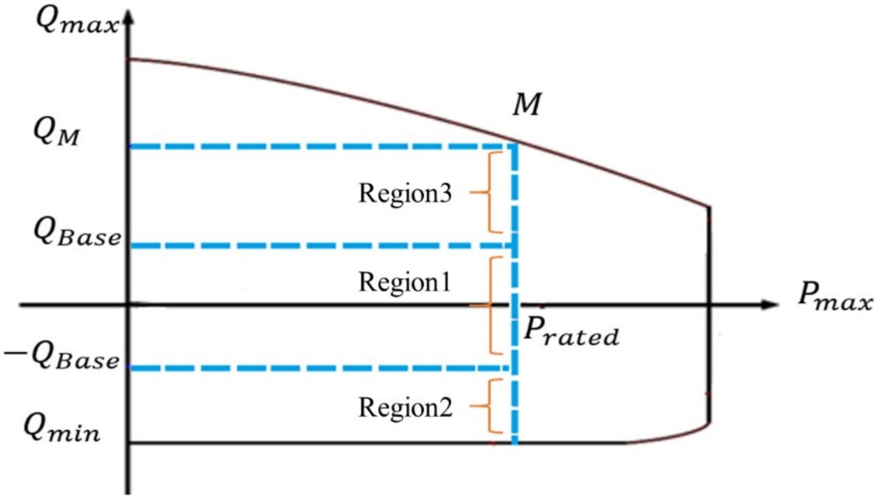

Fig. 5. Wind generator capability curve

The current and voltage limits of the converter must be considered in the production of reactive power, also the allowable amount of reactive power generation is calculated from the following equations [20].

$$Q_{WT} = \min\{Q_c, Q_y\} \tag{10}$$

$$Q_c = \sqrt{(V_g I_{c,max})^2 - P_{WT}^2} \tag{11}$$

$$Q_y = \sqrt{(\frac{V_g V_{c,max}}{X})^2 - P_{WT}^2} \; - \; \frac{V_g^2}{X} \tag{12}$$

Where, X represents the total reactance of the WT transformer, the grid filters, and the reactance of the transformer adapting the WT's voltage to the grid voltage [22]. Other parameters are shown Fig.5 [20].

In the first region ($-Q_{base} to\ Q_{base}$), only the WT availability cost is paid to adjust the operating point of the converter at the request of the power system. But in the second region ($Q_{min} to -Q_{base}$), and third region ($Q_{base} to\ Q_M$), with the production of reactive power, the amount of active power production decreases and the losses of active power increase, so the cost of reactive power generation is paid to the generator [15,20].

$$\text{expected payment function (EPF)} = \gamma_0 + \int_{Q_{min}}^{-Q_{base}} \gamma_1 dQ_{WT} + \int_{Q_{base}}^{Q_M} \gamma_2 dQ_{WT} \tag{13}$$

γ_0 is the availability price, γ_1 is the price offer for operating in ($Q_{min} to -Q_{base}$), γ_2 is the price offer for operating in ($Q_{base} to\ Q_M$) [20]. The increase in losses in the converter can be modeled as follows [27,29].

$$loss_{wt}(s) = I_0 + I_v \times S_{wt} + I_R \times S^2{}_{wt} \tag{14}$$

I_0, I_V, and I_R are the coefficients of the loss curves denoting standby losses, voltage dependent losses and current dependent losses. In addition to the same curves provided for the additional active power loss of synchronous generators in section 2.4.1, some studies have presented the additional active power loss as the following model. [27]

$$Loss_{wt}(P_{wt}, Q_{wt}) = \begin{cases} x_1\ Percent\ of\ Q_{wt} & if\ y_1 Percent\ of\ Q_{max} \le |Q_{wt}| \le y_2 Percent\ of\ Q_{max} \\ x_2\ Percent\ of\ Q_{wt} & if\ y_2 Percent\ of\ Q_{max} < |Q_{wt}| \le y_3 Percent\ of\ Q_{max} \\ x_3\ Percent\ of\ Q_{wt} & if\ y_3 Percent\ of\ Q_{max} < |Q_{wt}| \le y_4 Percent\ of\ Q_{max} \\ x_4\ Percent\ of\ Q_{wt} & if\ y_4 Percent\ of\ Q_{max} < |Q_{wt}| \le y_5 Percent\ of\ Q_{max} \end{cases} \tag{15}$$

4.4.3. Cost function of PV

The cost function of PV includes the costs of operation and maintenance (O&M). (the initial investment costs and land costs of the power plant has no effect on MG's bidding.) [30].

$$C_{pv} = G_{pv} \times S \tag{16}$$

Electronic converters can control the active and reactive power output of PV [30]. Reactive power generation reduces the amount of active power generation and increases power losses in the converter. It is expressed in Eq. (17).

$$Q = \sqrt{s^2 - p^2} - loss \tag{17}$$

The converter losses can be decomposed into conduction losses and switching losses. The conduction losses from current flow through switches and switching losses are turn-off and turn-on losses. Eq. (18) provides an estimate of inverter losses (the same as Eq. (14)) [27,29].

$$loss_{pv}(s) = I_0 + I_v \times S_{pv} + I_R \times S^2{}_{pv} \tag{18}$$

In designs, it should be noted that the amount of reactive power is directly related to the voltage and the range of voltage is limited.

2.5. Uncertainties

Use of RES due to the forecast of wind speed and solar radiation, increases uncertainties. These uncertainties influence MG's decisions. Previous studies have used different types of PDFs such as Gumbel, Weibull, Lognormal and Beta to model these uncertainties. In this paper, Weibull distribution is used to model wind speed and Beta distribution is used to model solar radiation.

2.5.1 Photovoltaic system uncertainties

By changing the solar radiation, the amount of electrical power output of these panels also changes. Usually predicting the amount of solar radiation is uncertain. Beta PDF can use to estimate solar radiation model. This function is represented in Eq. (19) [30].

$$f_{gs} = \begin{cases} \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\, r^{(\alpha-1)}(1-r)^{\beta-1} & ,0 \le r \le 1\,,\alpha \ge 0, \beta \ge 0 \\ 0 & ,\ other\ wise \end{cases} \tag{19}$$

μ: Average solar radiation

σ: Standard deviation of solar radiation

$$\beta = (1-\mu)\frac{(\mu\times(1-\mu)}{\sigma^2} - 1 \tag{20}$$

$$\alpha = \frac{\mu \times \beta}{1-\mu} \tag{21}$$

The output power from PV for a solar irradiation is described in Eq. (22) [17].

$$E_{pv} = E_{pvr} \times \frac{r}{r_{std}} \qquad \text{solar irradiation level W/ m2} \tag{22}$$

2.5.2. Wind uncertainties

Wind turbines convert wind into electrical energy. As the wind speed changes, so the outputs of these generators changes. Usually predicting the wind speed is uncertain. Weibull PDF can use to estimate solar radiation model. This function is represented in Eq. (23) [30,31].

$$f_{gw} = (\frac{k}{c}) \times \left(\frac{v}{c}\right)^{k-1} \times \exp\,(-\left(\frac{v}{c}\right)^{k}) \tag{23}$$

C (scale index): $\frac{2}{\sqrt{\pi}} \times v_{ave}$ (v_{ave}: Average incident wind speed at a particular location)

The output power from a wind unit for different wind speeds is represented in Eq. (24).

$$p_{wt} = \begin{cases} 0 & v \le v_{in}\ \ or\ \ v \ge v_{out} \\ \dfrac{v - v_{in}}{v_r - v_{in}} \times p_{wr} & v_{in} \le v \le v_r \\ p_{wr} & v_r \le v \le v_{out} \end{cases} \qquad \text{wind speed level m/ s} \tag{24}$$

2.6. Objective function

To maximize profits, the difference between $revenue$ and $cost$ must be maximized. The objective function of this is as follows.

$$profit = \sum_{s=1}^{S} \pi(s) \sum_{T=1}^{24} \sum_{n=1}^{n} (revenue - cost\,) \tag{25}$$

$$revenue = revenue\ of\ active\ market + revenue\ of\ reactive\ market + revenue\ of AS\ markets \tag{26}$$

$$revenue\ of\ active\ market = \ (\gamma_s^E \times P_n^E) \tag{27}$$

$$revenue\ of\ reactive\ market = \ \left(\gamma_Q \times Q_n\right) \tag{28}$$

$$revenue\ of AS\ markets = \begin{bmatrix} \left(o\gamma_{ru,s} \times P_{n,s}^{ru}\right)\ + \lambda_{ru}\left(\gamma_{ru,s} \times P_{n,s}^{ru}\right) \\ + \left(o\gamma_{sp,s} \times P_{n,s}^{sp}\right)\ + \lambda_{sp}\left(\gamma_{sp,s} \times P_{n,s}^{sp}\right) \\ + \left(o\gamma_{ns,s} \times P_{n,s}^{ns}\right) + \lambda_{ns}\left(\gamma_{ns,s} \times P_{n,s}^{ns}\right) \\ +\left(o\gamma_{rd,s} \times P_{n,s}^{rd}\right) + \lambda_{rd}\left(\gamma_{rd,s} \times P_{n,s}^{rd}\right) \end{bmatrix} \tag{29}$$

$$cost = \begin{bmatrix} \left(1 - \lambda_{ru} - \lambda_{rd} - \lambda_{sp}\right) \times C_n\ \left(P_{n,s}^E, Q_n\right) \\ +\lambda_{ru} \times C\ _n\left(P_{n,s}^E + P_{n,s}^{ru}, Q_n\right) \\ +\left(\lambda_{sp} - \lambda_{ns}\right) \times C\ _n\left(P_{n,s}^E + P_{n,s}^{sp}, Q_n\right) \\ + \lambda_{ns}\ \times C\ _n\ \left(P_{n,s}^E + P_{n,s}^{sp} + P_{n,s}^{ns}, Q_n\right) \\ + \lambda_{rd}\ \times C_n\ \left(P_{n,s}^E - P_{n,s}^{rd}, Q_n\right) \end{bmatrix} \tag{30}$$

The objective function consists of two parts. In the first part, the revenue and in the second part, costs are stated. The first part consists of three main Subsection as Eq. (26). As described in Eq. (27) revenue of active power market is equal to the amount of energy multiplied by its price. Eq. (28) is illustrates the relation for calculating reactive power profitability is the same as the active power relation. Revenue of AS markets (Eq. (29)) has four parts (each line is one part) and each part is related to one type of AS (regulation up, spinning reserve, non-spinning reserve and regulation down, respectively) and each part includes two term. The first term is the revenue of the AS contract and the second is the call of AS, this point is explained in *2.3.* AS call coefficient indicates the probability of needing each of the AS and determines the profit from the call of AS. For example, in section 3.3.2 for ERCOT market, this coefficient is calculated.

The MG cost section consists of five parts (each line is one part). These parts illustrate cost of participation in EM, participation in EM and regulation up, participation in EM and spinning reserve, participation in EM and spinning reserve and non-spinning reserve and participation in regulation down, respectively.

The first term presents the cost of participating in the EM. If the MG participates simultaneously in any of the other markets, the amount of energy produced changes, so the coefficient of this term is always less than or equal to one and is only for participation in the EM.

In the second term, the participation of the MG in the energy and regulation up market is modeled. If the MG participates in the regulation up market, the amount of power in the market will be added to the production capacity in the EM. The coefficient of this term is indicating the probability of this AS, and in other times, the cost is calculated from the first term.

The third and fourth terms are the same as the second term for spinning reserve and non-spinning reserve. The coefficient of the third term model that with the beginning of participation in the non-spinning reserve market, participation in the spinning reserve market does not stop so in the fourth term, the amount of participation in the spinning reserve and non-spinning reserve market is added to the total production capacity.

The fifth term is the same as the previous terms, but the capacity to participate in the regulation market is reduced from the total production capacity. In all terms, the cost of reactive power generation is added to the total cost. Equation (31) models this cost. [32]

$$C(Q) = (\gamma^E \times \Delta p \times \Delta t - oc)/(kvarh) \tag{31}$$

Δp is the amount of active power reduction, Δt is the duration of this reduction and oc is the cost of producing the same amount of active power in the same duration for the MG.

2.7. Risk management

Uncertainties of wind speed, solar radiation, energy prices, and AS influence the decision on participation of MG. In market conditions, these uncertainties can be managed in different ways, for this purpose, the CVaR method can be used. Currently, the CVaR is widely used because, besides being a coherent risk measure, it can be expressed using a linear formulation [33,34]. CVaR index is added to the objective function and controls the effect of uncertainties on the objective function. Normally the confidence level is assumed to be between 0.9 and 0.99. CVaR is presented as follows [18,35]:

$$var = var - 1/(1-\delta) \times \sum_{s=1}^{s} \pi_s \times \eta_s \tag{32}$$

$$var - profit_s \leq \eta_s \tag{33}$$

$$\eta_s \geq 0 \tag{34}$$

The cost function changes as follows in Eq. (35)

$$maximize = w \times profit + (1-w)\ cvar \tag{35}$$

2.8. constraint

2.8.1. Grid and generators constraint

Equations (36) - (37) present the limitation of apparent power and active power for each generator. There is a relationship between voltage and reactive power. Therefore, to prevent overvoltage of the MG, the maximum reactive power of each unit must be limited. Fig.6 illustrates some sample curves of voltage and reactive power [36,37].

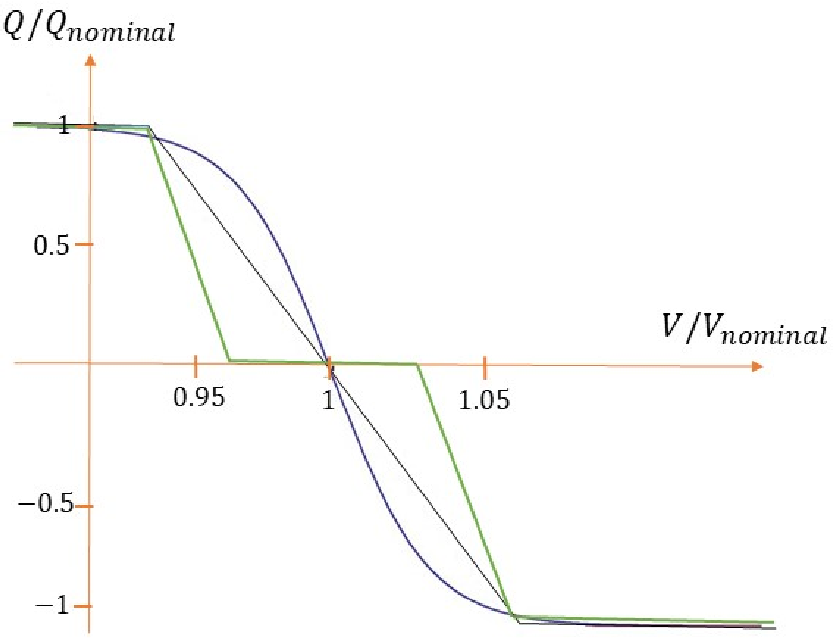

Fig. 6. Voltage and reactive power curve

These constraints exists in the Eqs. (38) and (39). Equations (40-44) indicate the amount of participation in each market cannot be negative. Equation (46) presents total regulation down and minimum generation power must be less than EM participation. Equations (46) - (47) are used to model the ramp up/down constraints [38].

$$S_n^{min^2} \le (P_n^E + P_n^r + P_n^s + P_n^{sp} + P_{loss})^2 + Q_n{}^2 \le S_n^{max\ 2} \tag{36}$$

$$P_n^{min} \le P_n^E + P_n^r + P_n^s + P_n^{sp} \le P_n^{max} \tag{37}$$

$$Q_n^{min} \le Q_n \le Q_n^{max} \tag{38}$$

$$V_n^{min} \le V_n \le V_n^{max} \tag{39}$$

$$0 \le P_n^E \tag{40}$$

$$0 \le P_n^{ru} \tag{41}$$

$$0 \le P_n^{sp} \tag{42}$$

$$0 \le P_n^{ns} \tag{43}$$

$$0 \le P_n^{rd} \tag{44}$$

$$0 \le P_n^{rd} \le P_n^E - P_n^{min} \tag{45}$$

$$P_n^E(t) - P_n^E(t-1) \le UR_n \tag{46}$$

$$P_n^E(t-1) - P_n^E(t) \le DR_n \tag{47}$$

Equations (48) – (52) present the total amount of each market participation cannot exceed the grid requirement. That means grid can limit the amount of MG's participation in different markets. Equation (53) presents ensures that MG provides the reactive power required by the grid to maintain its reliability and power quality.

$$0 \le \sum_{n=1}^{n} P_n^E \le P_{req} \tag{48}$$

$$0 \le \sum_{n=1}^{n} P_n^{ru} \le P_{req}^{ru} \tag{49}$$

$$0 \le \sum_{n=1}^{n} P_n^s \le P_{req}^s \tag{50}$$

$$0 \le \sum_{n=1}^{n} P_n^{ns} \le P_{req}^{ns} \tag{51}$$

$$0 \le \sum_{n=1}^{n} P_n^{rd} \le P_{req}^{rd} \tag{52}$$

$$Q_{req} \le \sum_{n=1}^{n} Q_n \tag{53}$$

2.8.2. Storage constraint

In this paper, it is assumed that ESS does not operate in the reactive power market. Equation (54) models charge and discharge relationship with storage efficiency [11]. Equations (55) – (56) express limitation of charge and discharge and maximum amount of stored energy [28]. Equation (57) indicates the total amount of participation in the energy and AS market is less than the total storage capacity, and this amount cannot be negative. Equation (59) ensures that the ESS cannot charge and discharge at the same time [14].

$$P_{st}(t) = P_{st}(t-1) + \eta^{st} \times P_{st}^{sh} - \frac{P_{st}^{dsh}}{\zeta^{st}} \tag{54}$$

$$P_{st}^{sh} \le P_{st}^{sh(\max)} \times S_{sh} \tag{55}$$

$$P_{st}^{dsh} \le P_{st}^{dsh(\max)} \times S_{dsh} \tag{56}$$

$$P_{st} \le P_{st}^{\max} \tag{57}$$

$$0 \leq P_{st}^{E} + P_{st}^{r} + P_{st}^{s} + P_{st}^{sp} \leq P_{st} \tag{58}$$

$$S_{sh} + S_{dsh} \leq 1 \tag{59}$$

3. Case study

For the case study, the ERCOT market is examined based on data (energy and AS price, solar radiation, wind speed ...) of 16/8/2020 for all the mentioned markets. The reactive power market is assumed to be annual and the MG must produce a certain amount of reactive power per hour. The simulation results show the participation of each unit in each of the energy and AS markets and the amount of energy charge and discharge per hour. The Weibull and Beta PDF of the Texas region are used to scenario making of solar radiation and wind speed.

3.1. Basic data of MG

The proposed MG includes two MTs, WT, PV and ESS. The specification, economic and technical data of these units are representing in Tables 1–4.

Table 1. Data of photovoltaic system

parameter	value	unit
E^{max}	2	MW
Irradiance at STC	1000	W/m^2
G	7.5	$\$/MWh$

Table 2. Data for wind turbine

parameter	value	unit
E^{max}	1	MW
v_{in}	3	m/s
v_r	12	m/s
v_{out}	22	m/s
G	5.77	$\$/MWh$

Table 3. Data for MT units

parameter	MT1	MT2	unit
E^{max}	1	2	MW
E^{min}	0.2	0.4	MW
UR	0.5	1	MW
DR	0.5	1	MW
b_1	0.02	0.03	-
b_2	2	1.5	-
b_3	5	6	-

Table 4. Data for energy storage

parameter	value	Unit
$E_{st}^{sh\ \max}$	2	MW
$E_{st}^{dsh(\max)}$	2	MW
η^{st}	90	%
ζ^{st}	90	%
$E_{st}^{\max}$	6	MW

3.2. Weather data

The wind speed and solar radiation on 12th July 2020 [39] are indicated in Fig. 7 and Fig. 8. Three main scenarios of wind speed and solar radiation are indicated in Fig. 9 and Fig. 10. These scenarios are generated by using Weibull, and Beta PDFs.

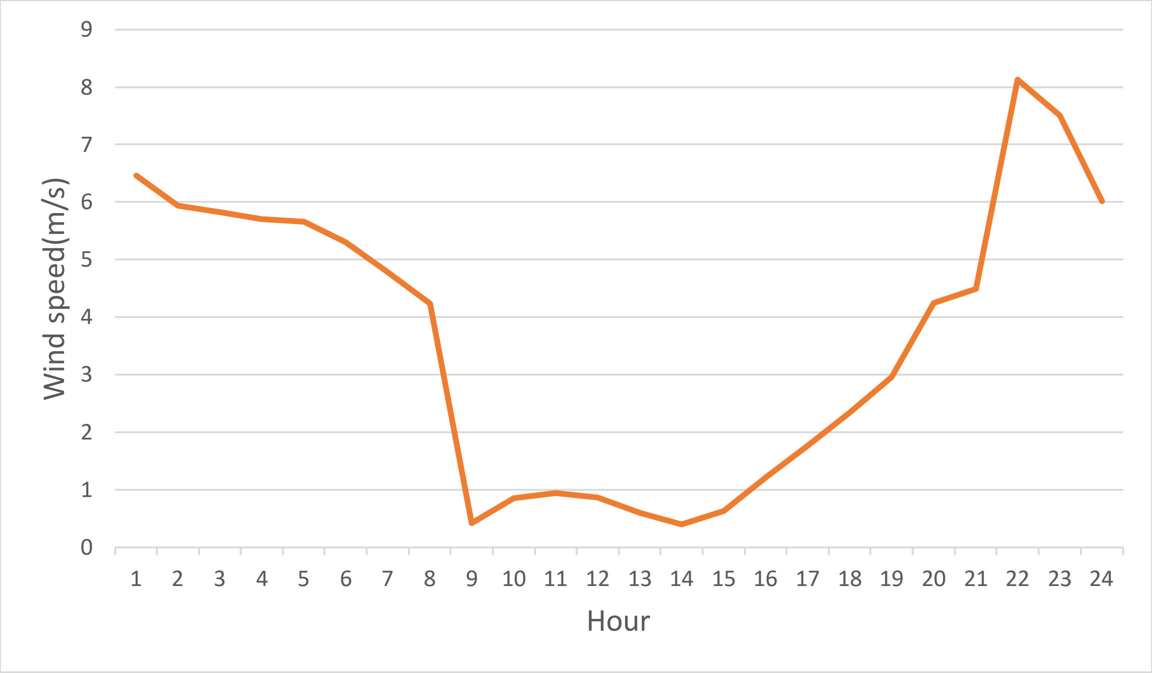

Fig. 7. Wind speed m/s

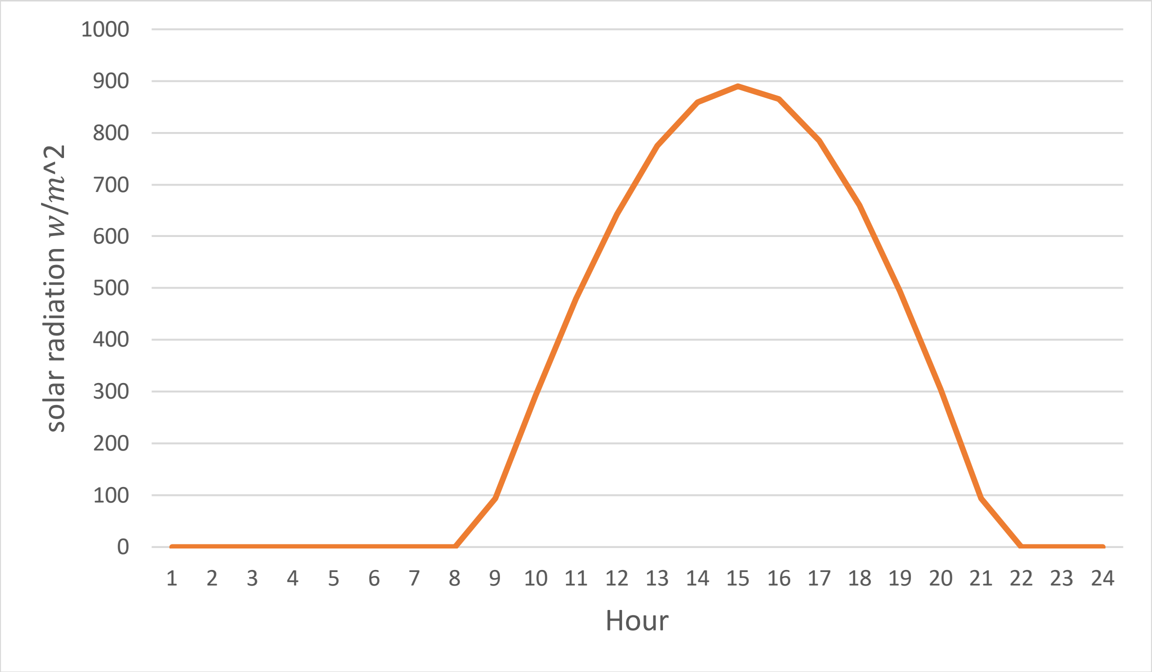

Fig. 8 Solar radiation w/m^2

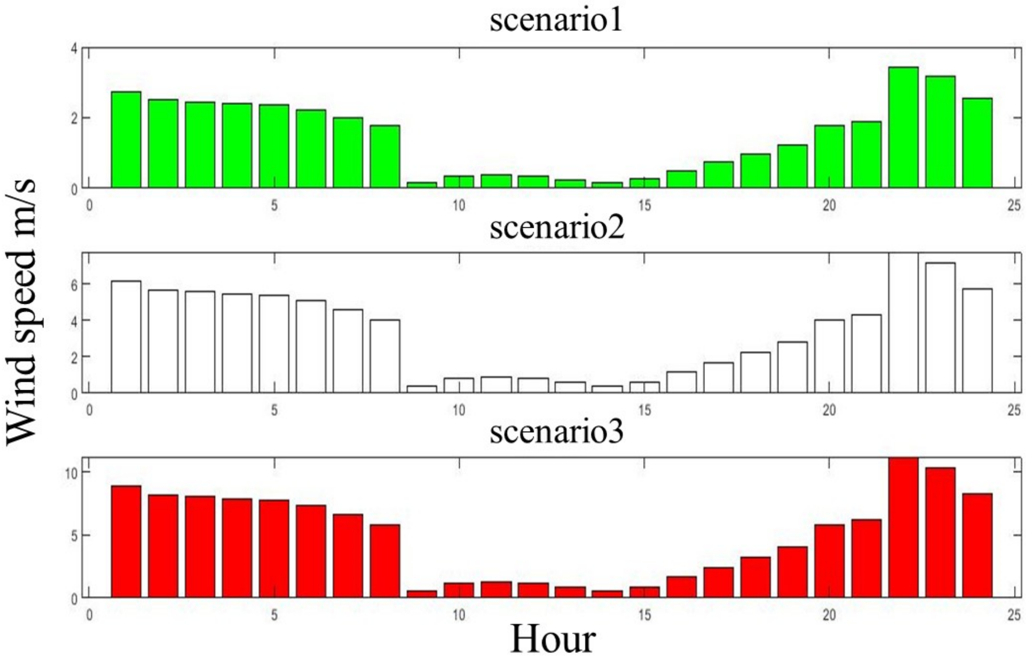

Fig. 9. Wind speed scenario m/s

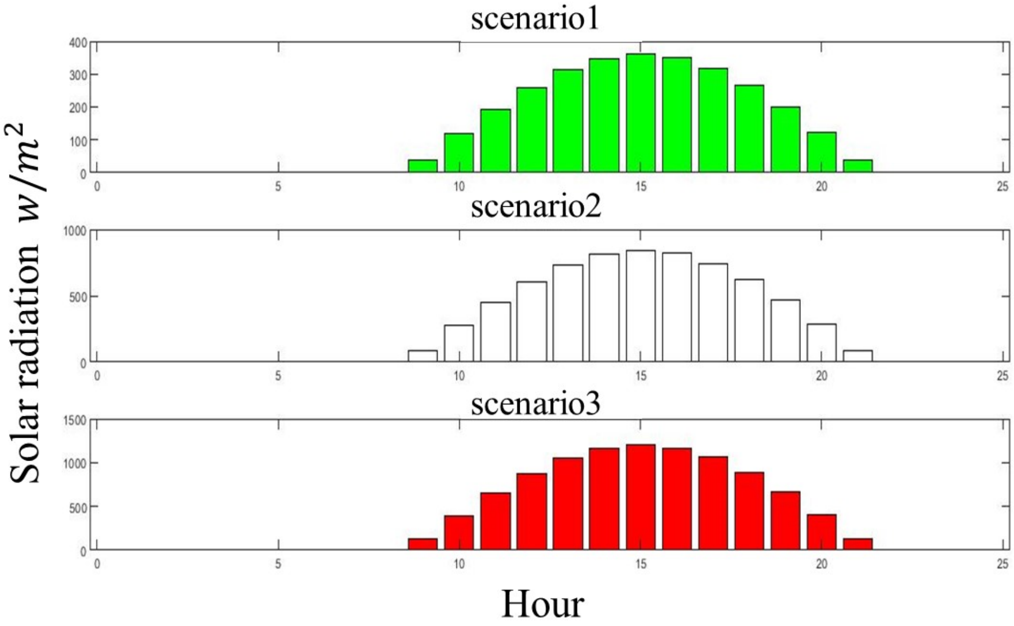

Fig. 10. Solar radiation scenario w/m^2

3.3. Data of market

In the ERCOT market, every day at 6 o'clock in the morning, the market operator publishes market's information. Participants then offer their participation in each of the markets before 10 o'clock. The market is active at 10 to 13:30 o'clock and then the results are announced [22].

3.3.1 Market price

Energy and AS prices and offer price of them for ERCOT market are present in Fig. 11 and Fig. 12 [26,40].

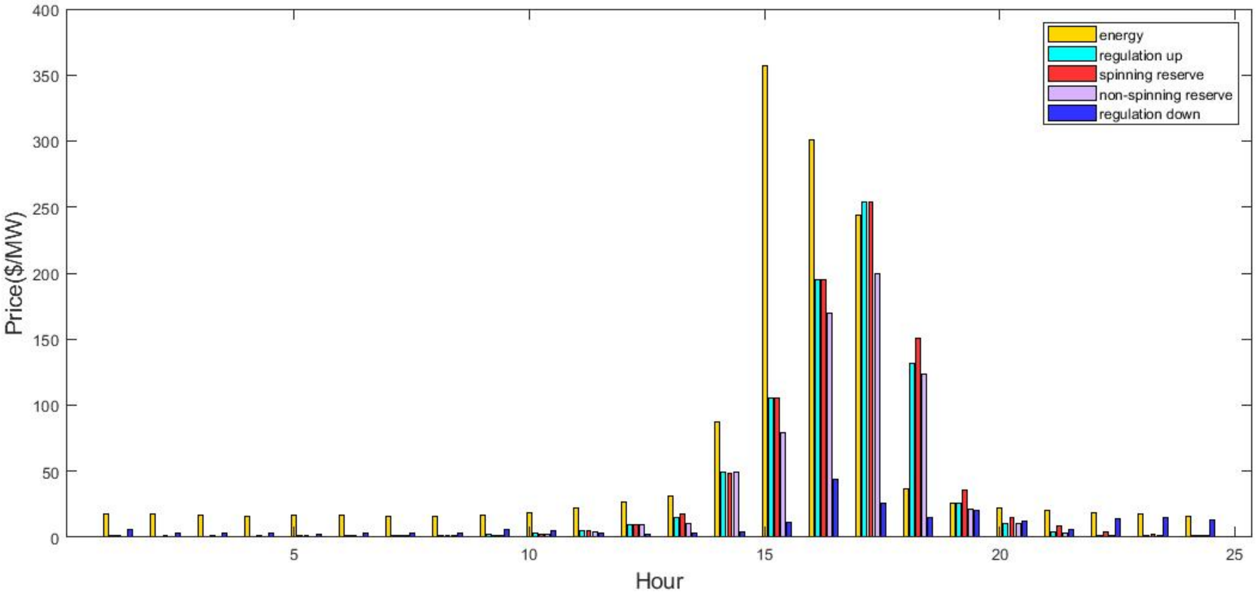

Fig. 11. Energy and AS price ($/MWh)

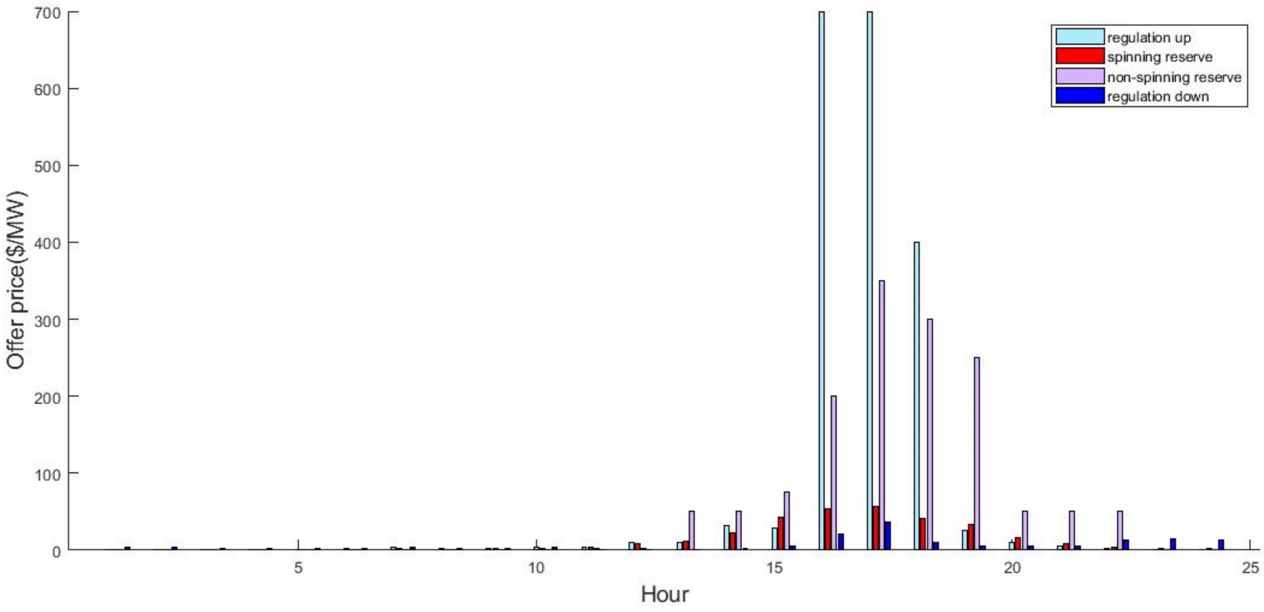

Fig. 12. AS offer price ($/MWh)

3.3.2. Probability of calling AS

Every year, the market operator publishes information of energy and AS consumption. Fig. 13 illustrates the average need for AS in July in the ERCOT market [26,40].

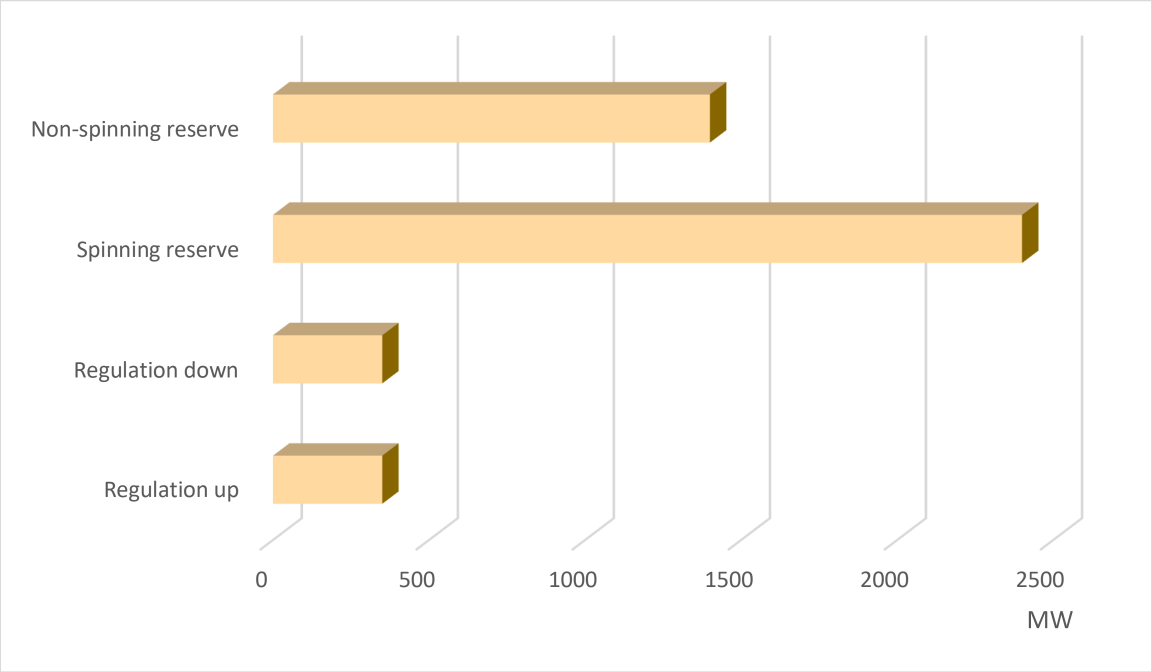

Fig. 13. Average need of AS in July for ERCOT market

Probability of calling AS can be calculated from the ratio of the need for AS to the average consumption of electricity per hour.

$$\lambda = \frac{\text{hourly average AS requirement}}{\text{average hourly energy consumption}} \tag{60}$$

The probability of calling AS data is provided in Table 5.

Table 5. Probability of calling AS

Type of AS	λ
Regulation up	0.0069
Regulation down	0.0067
Spinning reserve	0.055
Non-spinning reserve	0.032

3.4. Result

Fig. 14 illustrates the contribution of each unit to supply reactive power. It is supposed that the reactive power contract is annually and it equals to 300MW per hour. In the early hours of the day, due to low energy prices and fuel costs of MTs, they are more inclined to participate in AS markets, but as energy price rises, the EM is more profitable for MTs than the AS market. In the early hours of the day, PV generation is zero, so it has no participation in the reactive power market. Due to the difference in the cost function of the first and second MT, the behavior of these two generators is also different. Fig. 15 indicates the operating cost of the two generators. It is clear that due to the high operating cost of the second generator, it has more participation in the AS market.

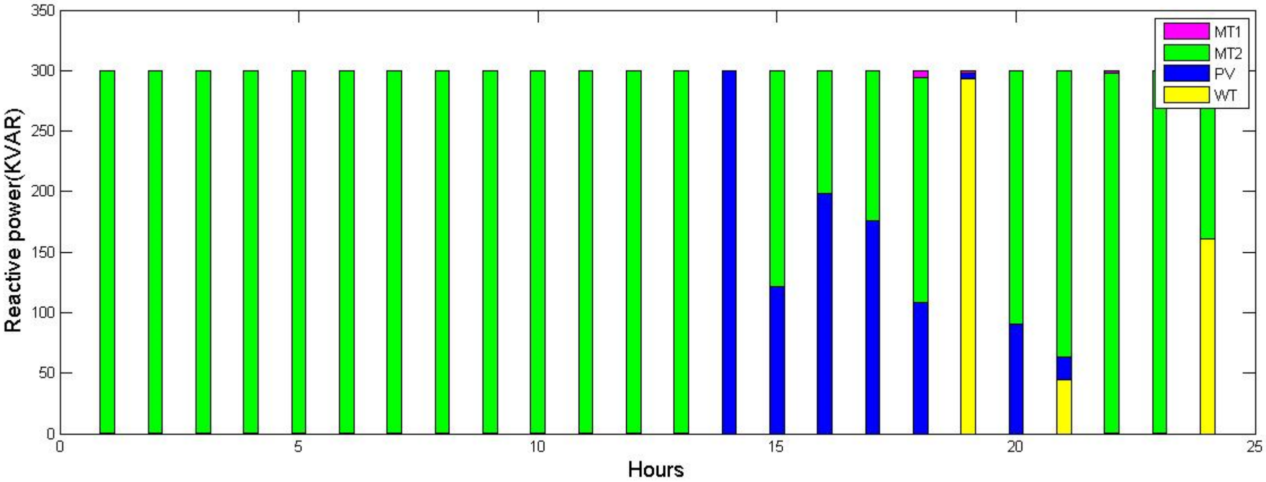

Fig. 14. Generators participation in reactive power market

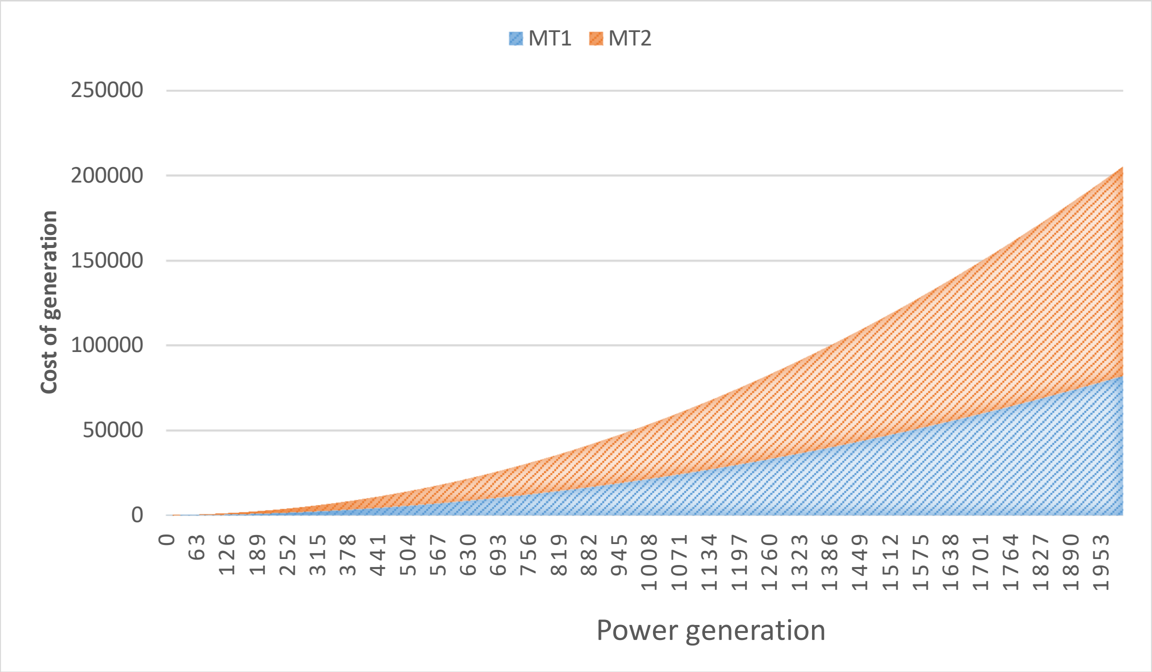

Fig. 15. Operation cost of MT1 and MT2

Fig. 16-19 present the participation of each unit in the energy and AS market and energy storage per hour. It is clear that RES has more participation in the EM at all hours due to low operating costs, but MTs participate more in the AS markets, and as energy prices increase, their participation in the EM increases.

As mentioned, MTs tend to participate in the AS markets. The price of regulation up is higher than other AS and its probability of call is less than other AS, so the MT2 has the highest participation in this market. Because of MT1's lower operation cost than MT2, it has more participation in EM. Usually, MT2 is operating in the EM with the minimum amount of power, so according to Eq. (45), cannot participate in the regulation down market.

Fig. 18 and Fig. 19 illustrate because of low operation cost of RES have the highest participation in EM but at 18 o'clock because of high price of spinning reserve PV participate in this market. Since the price of energy in the afternoon is higher than in the morning, these generators store part of their production capacity during these hours and offer it at expensive hours.

Table 6 presents the storage state at the end of each hour and Fig. 20 presents the ESS participation in energy and AS markets. In the hours when energy is cheap, the MG stores electricity and sells it in the hours when prices are high. The price of energy price at 14 to 18 hours is the highest point, and the stored electrical energy is sold at the same hours.

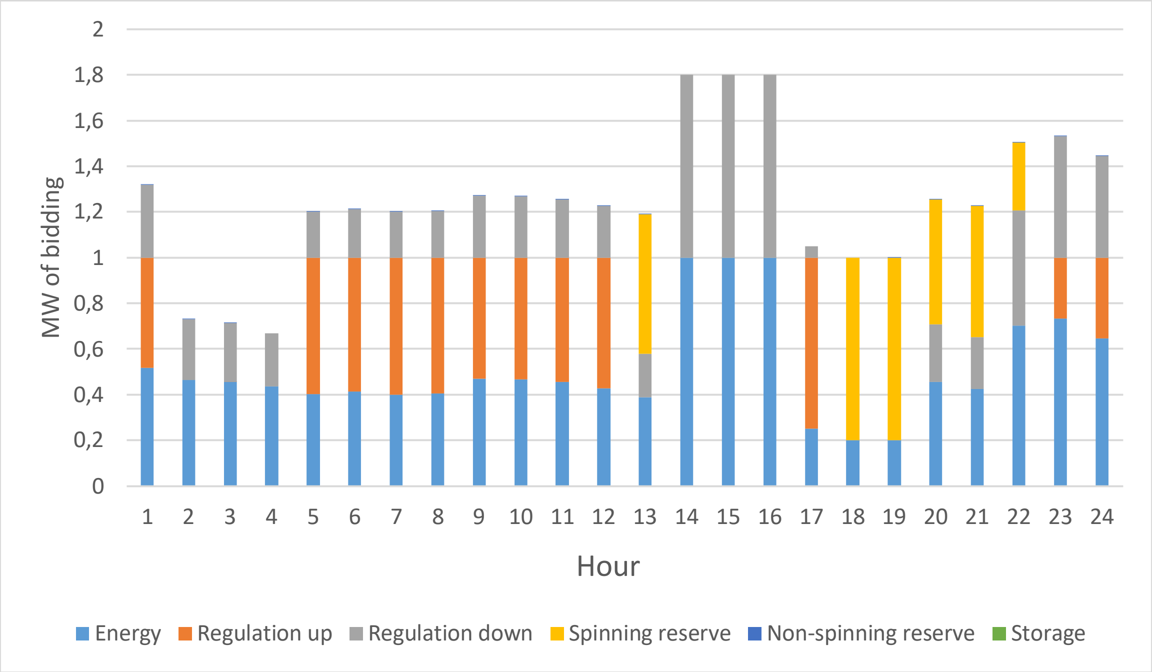

Fig. 16. MT1 bidding in energy and ASs markets and stored energy

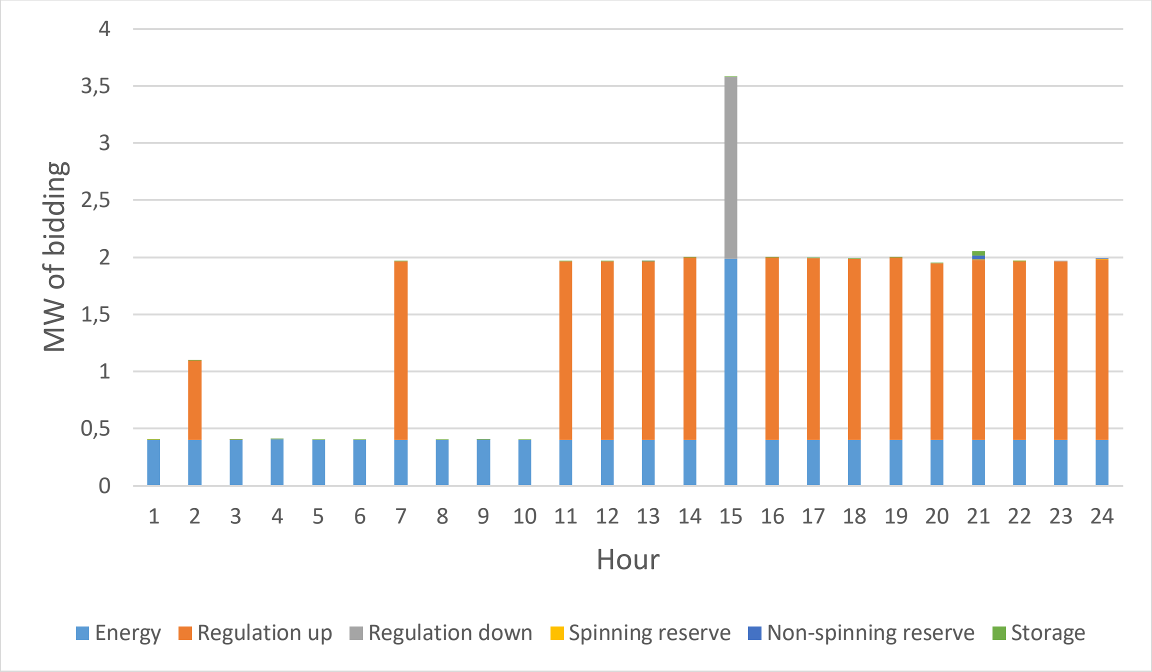

Fig. 17. MT2 bidding in energy and ASs markets and stored energy

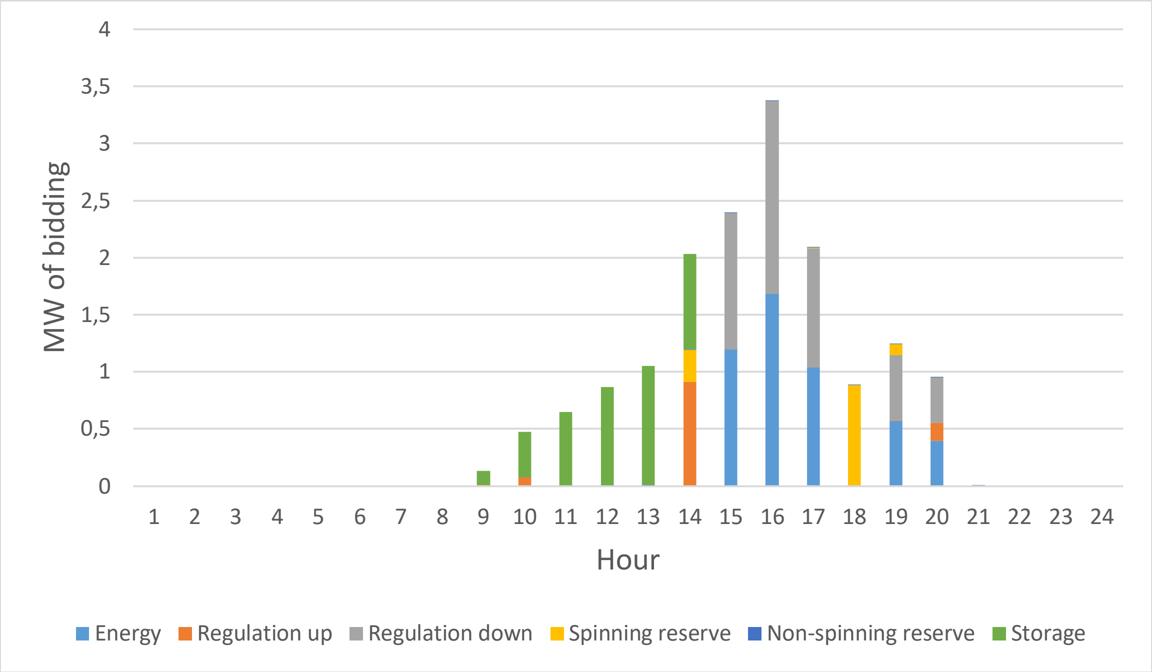

Fig. 18. PV bidding in energy and AS markets and stored energy

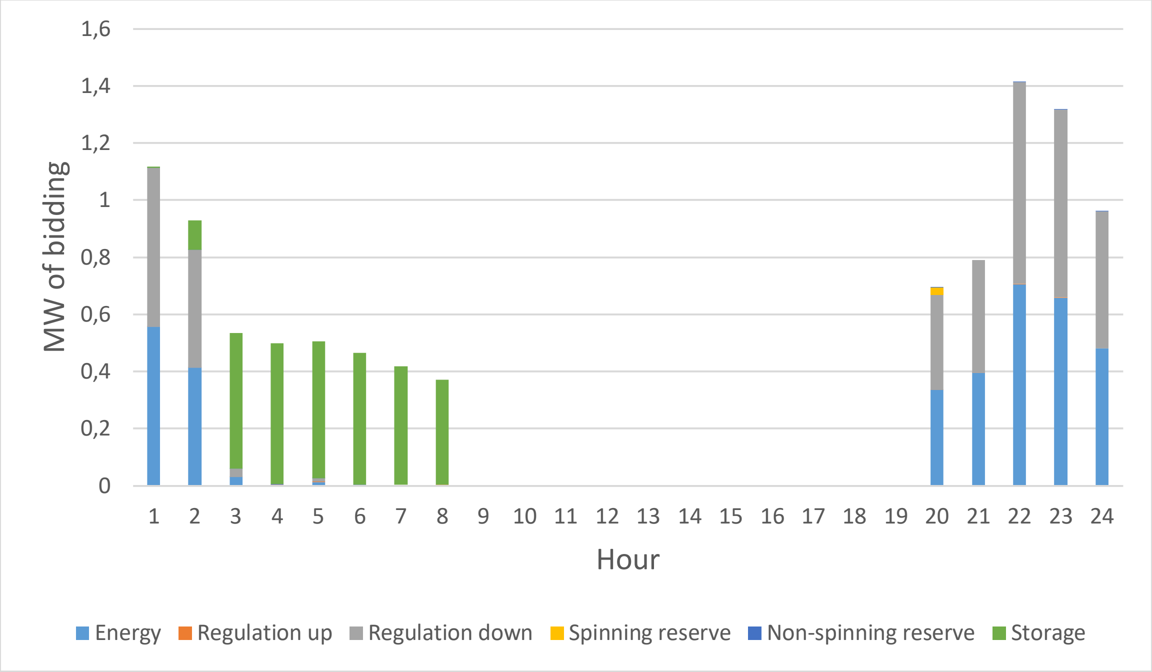

Fig. 19. WT bidding in energy and AS markets and stored energy

Table 6. storage state at the end of each hour

Hour	Storage state
1	0.0664
2	1.6035
3	8.7325
4	16.1423
5	23.3109
6	30.2257
7	35.7899
8	41.2945
9	43.2218
10	49.1615
11	58.9038
12	71.8262
13	87.4432
14	100.0000
15	66.6667
16	33.3334
17	0
18	0
19	0
20	0
21	0
22	0
23	0
24	0

According to Table 4 and Eq. 52 and Eq. 53, the amount of charge and discharge of the energy storage is limited. In the absence of this limitation, the MG will sell all its storage at 15 o'clock at the highest energy price. Also, due to storage losses, the amount of energy discharged is less than the storage capacity (6MW).

The graphical model in Fig.21 describes considered MG and its different units' participation in different markets and summation of them at 15 o'clock. Table 7 presents the total MG's participation in all markets. With the increase in energy prices, the amount of participation in the EM increases from 14 to 18 o'clock.

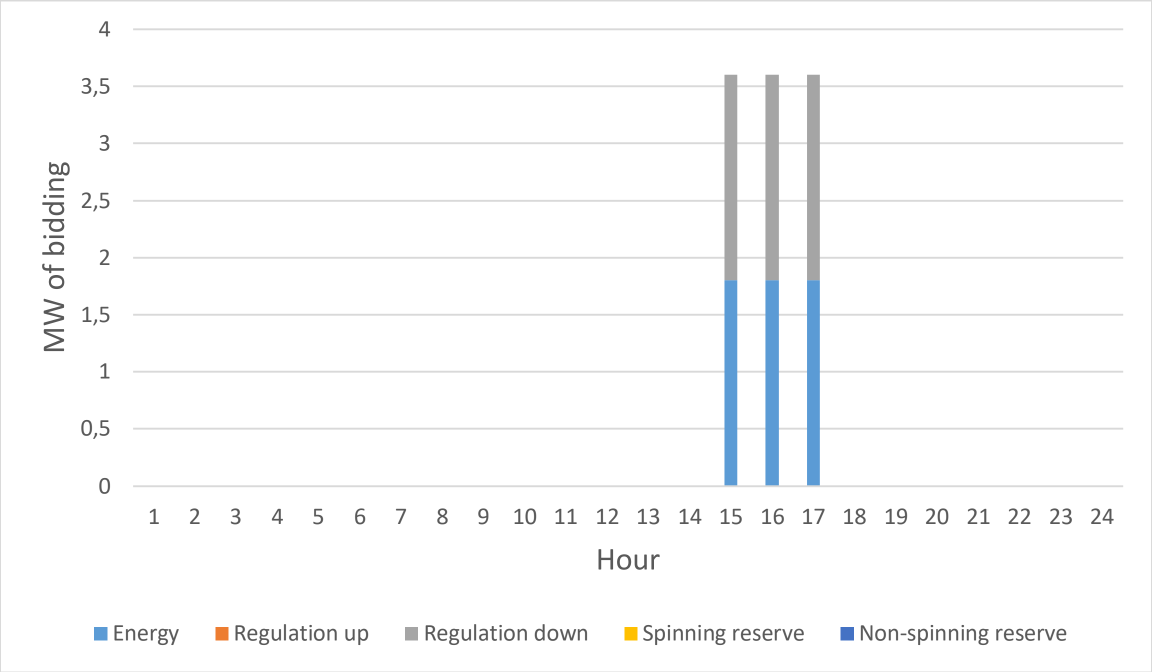

Fig. 20. ESS bidding in energy and AS markets

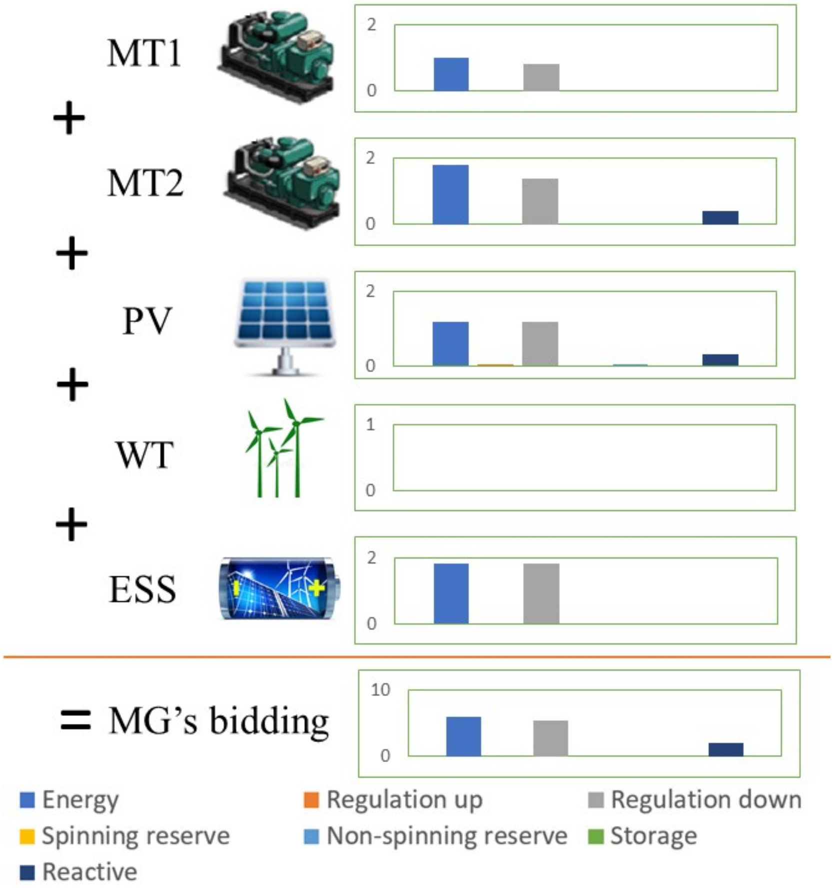

Fig. 21. Graphical model of MG's bidding strategy at 15 o'clock

Table 7. MG bidding in energy and ASs markets and stored energy

Hour Market	Energy	Regulation up	Regulation down	Spinning reserve	Non-spinning reserve	storage
1	1.4747	0.4819	0.8747	0.0007	0.0000	0.0044
2	1.2772	0.6953	0.6772	0.0000	0.0000	0.1025
3	0.8864	0.0008	0.2864	0.0000	0.0000	0.4753
4	0.8387	0.0000	0.2387	0.0000	0.0000	0.4940
5	0.8153	0.5978	0.2153	0.0000	0.0000	0.4779
6	0.8129	0.5871	0.2129	0.0000	0.0000	0.4610
7	0.8367	2.1629	0.2367	0.0000	0.0000	0.4150
8	0.8047	0.5953	0.2047	0.0000	0.0025	0.3670
9	0.8705	0.5295	0.2705	0.0000	0.0000	0.1285
10	0.8678	0.5323	0.2678	0.0000	0.0004	0.3961
11	0.8552	2.1083	0.2552	0.0000	0.0000	0.6495
12	0.8272	2.1357	0.2272	0.0000	0.0007	0.8615
13	0.7895	1.5636	0.1895	0.6108	0.0000	1.0415
14	1.4000	1.6009	0.8000	0.2847	0.0000	0.8371
15	6.0023	0.0000	5.4023	0.0000	0.0000	0.0000
16	4.9051	1.5968	4.3051	0.0000	0.0000	0.0000
17	1.6908	4.1586	1.0908	0.0101	0.0000	0.0000
18	0.6000	1.5871	0.0000	1.6848	0.0002	0.0000
19	1.1719	1.6000	0.5719	0.8960	0.0000	0.0000
20	1.5866	1.5490	0.9866	0.5688	0.0345	0.0000
21	1.2214	1.5769	0.6214	0.5748	0.0000	0.0000
22	1.8095	1.5613	1.2095	0.2988	0.0004	0.0000
23	1.8966	1.8302	1.2966	0.0000	0.0004	0.0000
24	1.5305	1.9350	0.9305	0.0048	0.0081	0.0000

Generator's participate in the regulation down market with all their power, because it does not increase their operating costs, but the power system needs for this AS should be considered for offers (in this simulation, there is no limit for it).

Fig. 22 illustrates the bidding curve of MG at 21 o'clock and Fig. 23 illustrates bidding curve of MT1 at 13 o'clock. It is clear that with the increase in energy prices, the participation rate in this market also increases, and in case of doubling the energy price, the participation rate of the first generator more than doubles.

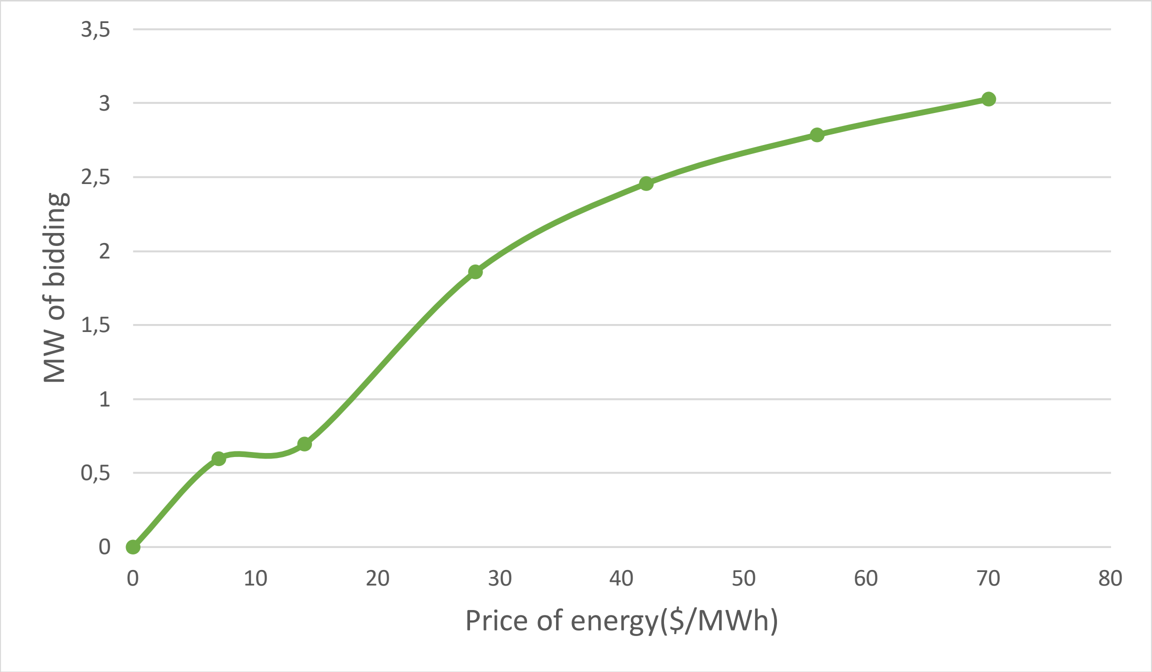

Fig. 22. Bidding curve of MG at 21 o’clock

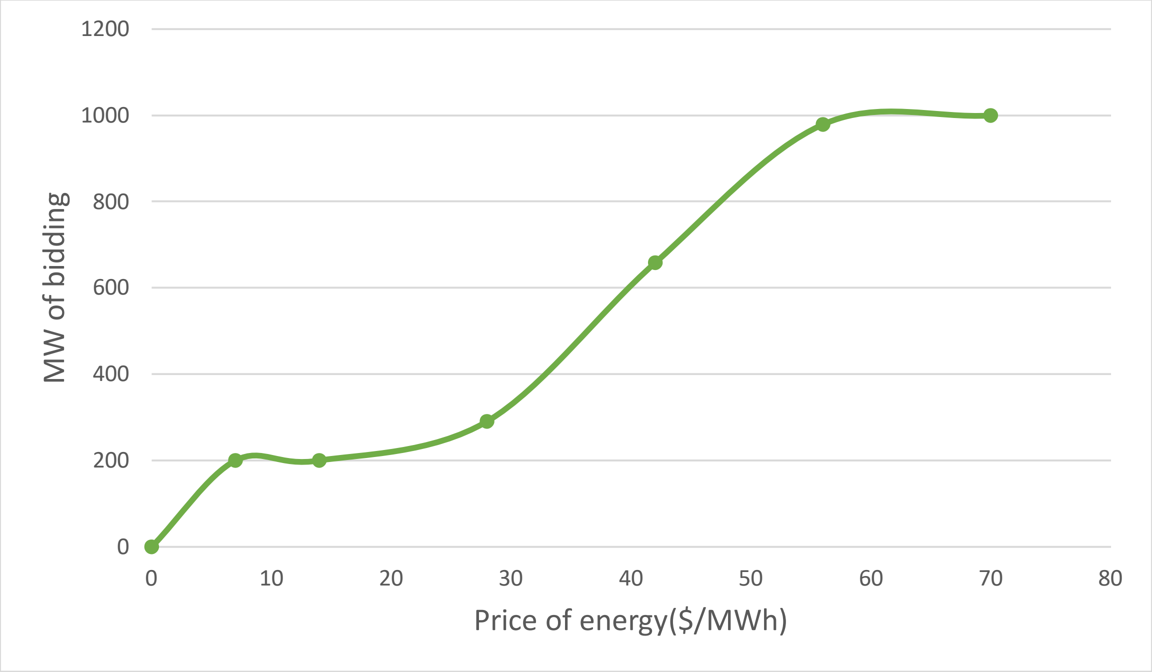

Fig. 23. Bidding curve of MT1 at 13 o’clock

4. Conclusion

AS are some essential services to maintain the reliability and stability of the system. The expansion of RES has increased the need for AS. In this paper, MG’s day-ahead optimal bidding strategy in joint active, reactive and AS market is modeled considering uncertainty of wind speed and solar radiation. The probability of calling AS is calculated and CVaR is used to control the risk of MG decisions. The simulation is based on real ERCOT market data. Expensive generators were more inclined to participate in the AS market and just participating in the EM when the price of energy is high. On the other hand, renewable generations because of their low operation cost have more participation in the energy markets. For the same reason and according to the capability curve, the participation of micro turbines in supplying reactive power is also greater than renewable products when energy price is low. According to the capability curve and mathematical equations, additional loss of production reactive power increased with increasing reactive power generation, so MG is trying to share reactive power generation between different sources. Probability of call AS changes MG's decisions. By reducing this coefficient, the generators online time decreased so expensive generators become more involved in AS markets. Results illustrate MG stored energy during off-peak hours, selling it during peak hours. Although part of the energy is wasted due to storage losses, the difference in energy prices compensated this energy loss. The bidding curve illustrates that with the increase in the price of energy, the participation of the MG in energy markets also increased. Finally, the authors of this paper think that by adding demand response programs, the quality of this paper will increase.

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