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ORIGINAL ARTICLE

Impact of Wind Energy on Marginal Cost in Electricity Markets

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ABSTRACT
Production of electrical energy from renewable sources has become one of the best ways to deal with shortage of fossil fuels, greenhouse gas emission and preventing global warming. One of the most important renewable energy is a wind energy which has great potential for electricity generation in most parts of the world. Renewable units having inherent irregularity and uncertainty, This thread often makes some difficulties to entrance the renewable resources into the planning. A wind turbine has varies instantaneous output power due to rapid changes in wind speed, it has led to that the wind turbines could not brought into the designs accurately and often to determination of these turbines output the wind speed should estimated based on probability density functions and ultimately mean value should be obtain from the output of a wind turbine. In this paper sampling of wind speed has been done by WEIBULL distribution and then by wind turbine power curve the obtained power output from each sample in the wind farm will be achieved. Also the impact of considered uncertainty in the wind power plants output on operating conditions and Marginal cost and also the need for preventive measures in order to deal with power fluctuations due to uncertainty will modeling using GAMS software. The overall results of the current study is significant impact of the wind units on utilization of power system, so that by increasing of wind power penetration coefficient in the system, the Marginal cost generally decrease in all buses.
Keywords: *Electricity market, wind energy, Marginal cost, uncertainty, GAMS.*

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INTRODUCTION

Using probabilistic criteria to determine the units commitment and their production power being taken into orbit has about 50 years of background. In numerous papers, the effect of production power of wind power plants joining the power system on production overall cost, sensitivity of Marginal cost to consumption amount, assessing produced scenarios to consider uncertainty of wind unit production, achieving the best pricing scenario for a wind producer in electricity market, modeling the units commitment program following strictly the net security considering uncertainty in production power of wind units and calculating the needed spinning and non-spinning reserve level in a power system with high penetration coefficient of wind potency, have been studied. For instance designating the capacity probabilistically and based on hazard analysis has been in use in PJM since 1975 [1]. In [2] the generalized model of units commitment program has been noticed. In the model said in this paper, some limitations such as fuel limitation in heat units as well as energy limitation in hydro electricity units have been considered. Reference [3] has presented a method to consider the generator reliability in timing the units in competitive structure of the market simultaneously for both energy and reserve. In [4] a method to control the amount of spinning reserve based on the probable assessment for the needed reserve has been studied. In this reference, the reliability of the units has been taken into account and the uncertainty in the prediction of charges has been considered for the short term timing of the units. [5] is a method to determine the most economic model to units commitment regarding specific level of reliability. In [6] the liquidation of the market that is following the system reliability in Laver market environment has been studied in the form of unit commitment. In [7] the modeling of market liquidation has been studied periodically as an uncertain problem following the limitations. In this reference, optimizing the reserve amount has been done by using the penalty factor for mathematics hope of the lost charge. [8] works out the model presented in [7] regarding uncertainty conditions or security limits such as lines thermal limit, lines and units stop, charge fluctuations etc.

[9] suggests a method to calculate the optimum spinning reserve amount for accidental situations. The uncertainties such as units stop, error in predicting charge amount and wind units production are included in this reference. This reference to perform uncertainty has used Mont Carlo simulation and has compared it with the time that there is no uncertainty.
On the other side, using renewable energies like wind and sun leads to considerable new uncertainty in the system because of various nature of them as well as the fact that the existing measuring devices can not accurately do it and this conditions make the determination of the reserve appropriately to manage the system be necessary [9].
Due to the new conditions in operating power systems and improving calculating tools, in recent years great efforts have been made to arrange the probable units commitment and their power production and in a restructured environment and new methods have been presented for this purpose.
Reference [10] has studied the market liquidation the other day regarding uncertainty of the wind power plants with high penetration coefficient. This reference suggests that market liquidation strictly following security and uncertainty compared to market liquidation considering the worst security operation, allows the operator more to use wind units and as a result causes the penetration coefficient of the wind units in power systems to grow up. Reference [11] presents a model in which to solve the problem of units commitment program following security, has used demand responding and its timing as the needed reserve for the system in electricity wholesale market. In this reference, providing reserve happens by the help of units as provider of the demand response that is responsible for aggregating and managing demand response.
In reference [12] a model to calculate the power system reliability cost has been presented on the basis of solving the long term problem of plants commitment following security considering uncertainty of units and lines stop and also error in charge prediction. In this reference, scenario tree has been used to consider uncertainty scenarios in the context of Mont Carlo simulation.
So, the units commitment program when wind production is high within the system, considering uncertainty in wind prediction, will be solved and modeled.
In this paper, the modeling purpose is to use wind production power in the other day operation of a network when production power of wind power plants is uncertain. Operating the system considering the high penetration coefficient of wind power plants (uncertainty in wind power plants output) will be modeled as plants commitment program. Moreover the effect of using wind potency and increasing their penetration coefficient on marginal cost will be surveyed. In the second part the effects of using wind potency on system has been studied and the way of producing scenarios of wind power to be used in modeling the plants commitment program considering uncertainty will be presented and modeling of network operation will be performed. Also in this part, the planning method in uncertainty environment and modeling the operation in this environment considering uncertainty in production potency of wind power plants will be surveyed. In the third part, scalar studies are presented and eventually in the fourth part conclusion and suggestions will be offered.

MODELING THE UNITS COMMITMENT PROGRAM CONSIDERING UNCERTAINTY

The wind power because of the wind having inherent accidental nature is not distributable to the traditional concept of it. Therefore the wind production has been changing and unspecific and as a result its over-aggregation and in large scale in a power system, has become a great challenge for power system operators and designers [13,14].
Method of producing scenario in some references [15,16], is so much easy and far from reality. Experience has shown that wind speed follows the WEIBULL distribution accurately. With this assumption the prediction error in wind speed should be made by WEIBULL distribution, wind potency scenarios to be created.
By incorporating auto regressive models and moving average, the model of ARMA will be as following:

$$y_t = \phi_1 y_{t-1} + \phi_2 y_{t-2} + \ldots + \phi_p y_{t-p} + \varepsilon_t - \theta_1 \varepsilon_{t-1} - \theta_2 \varepsilon_{t-2} - \ldots - \theta_q \varepsilon_{t-q} \quad (1)$$

In which y_t is the data conceived at the time t and ϕ are the related coefficients. ε_t is known as the residual of the model θ is the coefficient of the residual amounts in the model.

A time series of ARMA related to the accidental process of Y can be shown as following:

$$y_t = \sum_{j=1}^{p} \phi_j y_{t-j} + \varepsilon_t - \sum_{j=1}^{q} \theta_j \varepsilon_{t-j} \qquad (2)$$

In which p the auto regressive parameter $\phi_1, \phi_2, \ldots, \phi_p$ and q the parameter of moving average $\theta_1, \theta_2, \ldots, \theta_q$ have been used. In (2) equation, ε_t shows a normal accidental process with a zero average and variance of σ_ε^2 that is uncorrelated with $y_{t-1}, y_{t-2}, \ldots, y_{t-p}$.

WEIBULL distribution as a suitable distribution which describes wind speed with a good approximation has been widely accepted [17,18].

Since the accidental process used in ARMA model should have a normal distribution, to protect the nature of original limit distribution related to the accidental process of wind speed of Y when using ARMA model, a new accidental process of Z, will be defined by standard normal limit distribution as following Transformation:

$$Z = \Phi^{-1}\left[F_Y\left(Y\right)\right] \qquad (3)$$

In which F_y is cumulative distribution function of limit distribution related to original accidental process of Y and Φ(0) is cumulative distribution function of standard normal accidental variable.

Converting equation (3) has been shown in figure (1). In this figure, the direction called d, shows this conversion.

So ARMA model mentioned in equation (2) has been exerted on accidental process of Z and fitted model on the accidental process values of Z will be calculated. In this stage the auto regressive parameters of $\phi_1, \phi_2, \ldots, \phi_p$ and moving average of $\theta_1, \theta_2, \ldots, \theta_q$ will be calculated. Then using these parameters and error production and white noise, accidentally and based on normal distribution, wind speed scenarios in normal environment of Ω_z will be produced. Eventually using reverse conversion below, produced scenarios in normal environment will go to WEIBULL environment and wind speed value scenarios of Ω_y that show the original accidental process scenarios will be made [19,20].

$$Y = F_Y^{-1}\left[\Phi\left(Z\right)\right] \qquad (4)$$

This Transformation in figure 1 has been marked by i in the direction.

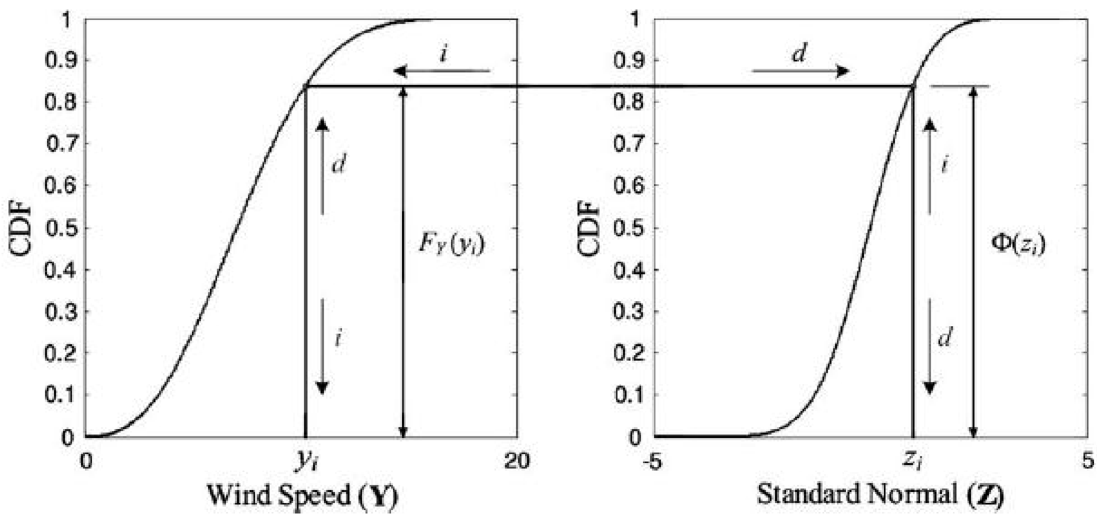

Figure 1: Transformation of accidental changing values of wind speed from WEIBULL environment to normal and vice versa [19,20]

After producing wind speed scenarios, should change into electrical power production to be used in accidental planning of power system operation. For this purpose, the curve of output potency of a sample wind turbine is used. This curve has been shown in figure (2).

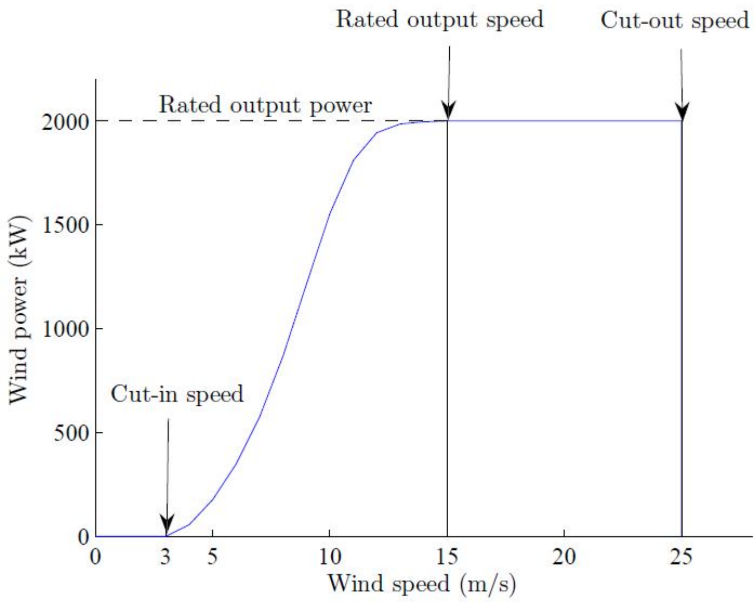

Figure 2: power curve of a sample wind turbine

In electricity market, social welfare will reach the peak in a day. The related target function will be as following:

$$\max SW = \sum_{t=1}^{T}(GS_t - OC_t) \tag{5}$$

In which:

t: is the index of operation period time in hour from 1 to T

GS_t gross surplus of consumer in t period

OC_t operation cost in t period

In this problem, the objective is to minimize paying to the thermal units for energy (C1) and reserve capacity (C2). C1 contains energy production cost and production units start up cost.

$$F1: \min\ OC = \sum_{t=1}^{T}\sum_{i=1}^{N_G}\left(\mathrm{C}1_{it}(p_{it}, u_{it}) + \mathrm{C}2_{it}(r_{it}^{up}, r_{it}^{dn})\right) \tag{6}$$

In which:

i index of power production units from 1 to N_G

P_{it} variable of power production decision of i unit in t period (MW)

u_{it} variable of binary decision showing commitment (1) or not commitment (0) of unit i in period t

r_{it}^{up} variable of increasing planned reserve capacity decision for unit i in hour t (MW)

r_{it}^{dn} variable of decreasing planned reserve capacity decision for unit in hour t (MW)

The cost of providing energy considered in target function (6), will be as following:

$$C1_{it}(p_{it},u_{it}) = suc_{it} + \sum_{k=1}^{N_{step}} \gamma_{ik}^{offer} p_{ikt}^{G} \quad ,\forall i,\forall t \tag{7}$$

In which:

γ_{ik}^{offer} proposed price for generator i in step k

p_{ik}^{G} i generator power production in step k

suc_{it} variable, start up cost of unit i in hour t

By such description of pricing method, the constraints related to a limitation in generator power production in each step and the overall power production of each generator will be as following:

$$0 \le p_{ik}^{G} \le \overline{p_{ik}^{G}} \quad ,\forall i,\forall k \tag{8}$$

$$p_{it} = \sum_{k=1}^{N_{step}} p_{ik}^{G} \quad ,\forall i,\forall t \tag{9}$$

In which $\overline{p}_{ik}^{G}$ is the maximum power production of i generator in k step

The other constraints of this model are:

$$\sum_{\substack{i=1\\ i:(i,n)\in M_G}}^{N_G} p_{it} - \sum_{\substack{j=1\\ j:(j,n)\in M_D}}^{N_D} P_{jt}^{D} + \sum_{\substack{q=1\\ q:(q,n)\in M_W}}^{N_W} \left(P_{qt}^{W} - S_{qt}^{W}\right) - \sum_{\substack{r=1\\ r:(n,r)\in \Lambda}}^{N_B} f_{nrt} = 0 \quad ,\forall n,\forall t \tag{10}$$

$$f_{nrt} = \frac{Ploss_{nrt}}{2} + B_{nr}\left(\delta_{nt} - \delta_{rt}\right) \quad ,\forall (n,r)\in\Lambda,\forall t \tag{11}$$

$$-\overline{f}_{nr} \le f_{nrt} \le \overline{f}_{nr} \quad ,\forall (n,r)\in\Lambda,\forall t \tag{12}$$

$$p_{it} + r_{it}^{up} \le u_{it} \times P_{i}^{\max} \quad , \forall i, \forall t. \tag{13}$$

$$u_{it} \times P_{i}^{\min} \le p_{it} - r_{it}^{dn} \quad ,\forall i, \forall t. \tag{14}$$

$$p_{it} - p_{i(t-1)} \le RUp_{i} \quad , \forall i, \forall t \tag{15}$$

$$p_{i(t-1)} - p_{it} \le RDn_{i} \quad , \forall i, \forall t \tag{16}$$

$$0 \le S_{qt}^{W} \le P_{qt}^{W} \quad , \forall q, \forall t \tag{17}$$

$$0 \le r_{it}^{up} \le \mathrm{MSR_i} \times \tau \quad \forall i, \forall t. \tag{18}$$

$$0 \le r_{it}^{dn} \le \mathrm{MSR_i} \times \tau \quad \forall i, \forall t. \tag{19}$$

$$(X_{i(t-1)}^{on} - \mathrm{mut_i}) \times (u_{i(t-1)} - u_{it}) \ge 0 \quad \forall i, \forall t. \tag{20}$$

$$(X_{i(t-1)}^{off} - \mathrm{mdt_i}) \times (u_{it} - u_{i(t-1)}) \ge 0 \quad \forall i, \forall t. \tag{21}$$

$$suc_{it} \ge \mathrm{suCost_i} \times (u_{it} - u_{i(t-1)}) \quad \forall i, \forall t. \tag{22}$$

$$u_{it} \in \{0,1\} \quad , \forall i , \forall t. \tag{23}$$

In which:

M_G matrix of correspondence between thermal units and buses

j index of system consumers from 1 to ND

M_D matrix of correspondence between consumers and buses

n,r index of system bases from 1 to NB

P_{it}^D charge of consumer i in t period

q index of wind units from 1 to NW

M_W matrix of correspondence between wind units and buses

P_{qt}^W power production of wind unit q in period t

S_{qt}^W cut power values from wind unit q production in period t

Λ system transmission lines set

f_{nrt} line transmission power between buses n and r in t period

$Ploss_{nrt}$ active power loss in the line between buses n and r in t period

$\bar{f}_{nr}$ maximum transmission power of the line between buses n and r

B_{nr} size of the imaginary admittance part of the line between buses n and r

δ_{nt} voltage angle of bus n in t period

P_i^{max} maximum power production of unit i

RUp_i power increasing rate of unit i in one hour

RDn_i power decreasing rate of unit i in one hour

MSR_i Maximum Sustained Ramp rate (MSR) the change of output power of unit i (MW/min)

τ time interval that the reserve should completely be at disposal (min)

mut_i minimum time of unit i being on

mdt_i minimum time of unit i being off

X_{it}^{on} number of hours of unit i being on

X_{it}^{off} number of hours of unit i being off

$suCost_i$ parameter, cost of start up of unit i

Line loss between buses s and r will be calculated as follows:

$$\begin{aligned} p_{sr}^{loss} &= p_{sr} + p_{rs} \\ &= 2g_{sr}\left[1-\cos\left(\delta_s - \delta_r\right)\right] \\ &\cong g_{sr}\left(\delta_s - \delta_r\right)^2 \end{aligned} \tag{24}$$

To model the market considering the target function uncertainty mentioned in equation (7) will be corrected as:

$$F2:\min\ OC = \sum_{t=1}^{T}\left\{\begin{array}{l}\sum_{i=1}^{N_G}\left(\mathrm{C}_1(p_{it},u_{it})+\mathrm{C}_2(r_{it}^{up},r_{it}^{dn})\right)\\ +\sum_{s=1}^{N_S} prob_s\cdot\left(\sum_{i=1}^{N_G}\mathrm{C}_3(\hat{r}_{it,s}^{up},\ \hat{r}_{it,s}^{dn},\ )+\mathrm{VOLL}_t\times\sum_{j=1}^{N_D} lns_{jt,s}\right)\end{array}\right\} \tag{25}$$

In which:

s index of the set of scenarios from 1 to Ns

$prob_s$ occurrence possibility of scenario s

$\hat{r}_{it,s}^{up}$ increasing reserve amount used for unit i in t period related to scenario s

$\hat{r}_{it,s}^{dn}$ decreasing reserve amount used for unit i on t period related to s scenario

$C_3(\cdot)$ cost function of using units reserves

$VOLL_t$ the value of one mega watt hour of lost load in t period

$\ln s_{jt,s}$ cut power amount of load j in t period related to scenario s

The limiting constraints below is added to determine power production value of thermal units:

$$p_{it,s} = p_{it} \quad , \forall\mathrm{i},\ \forall\mathrm{t},\ \forall\mathrm{s} \tag{26}$$

The equations (27) and (28) are added to the model to calculate and exert limitation in the amount of transmission power in lines in each of the scenarios.

$$\hat{f}_{nrt,s} = B_{nr}\left(\hat{\delta}_{nt,s}-\hat{\delta}_{rt,s}\right) \quad , \forall\left(n,r\right)\in\Lambda,\ \forall\mathrm{t},\forall\mathrm{s} \tag{27}$$

$$-\overline{f}_{nr} \le \hat{f}_{nrt,s} \le \overline{f}_{nr} \quad , \forall\left(n,r\right)\in\Lambda,\ \forall\mathrm{t},\forall\mathrm{s} \tag{28}$$

In which $\hat{\delta}_{nt,s}$ is the voltage angle of bus n in period t related to scenario s.

The equation related to maximum wind interruptible power in each scenario will be as:

$$0 \le \hat{S}_{qt,s}^{W} \le \overline{P}_{qt,s}^{W} \quad , \forall\mathrm{q},\ \forall\mathrm{t},\ \forall\mathrm{s} \tag{29}$$

The following constraints show maximum usable amount of increasing and decreasing reserve of each unit in every scenario:

$$0 \le \hat{r}_{it,s}^{up} \le r_{it}^{up} \qquad \forall i,\ \forall t,\ \forall s. \tag{30}$$

$$0 \le \hat{r}_{it,s}^{dn} \le r_{it}^{dn} \qquad \forall i,\ \forall t,\ \forall s. \tag{31}$$

CASE STUDY

The system used for studying operation and survey of the results in this part, is the 24 buses IEEE system. His system contains 33 generator and the maximum consumption power at 6 pm will reach 2850 mega watts. The figure below shows this sample network.

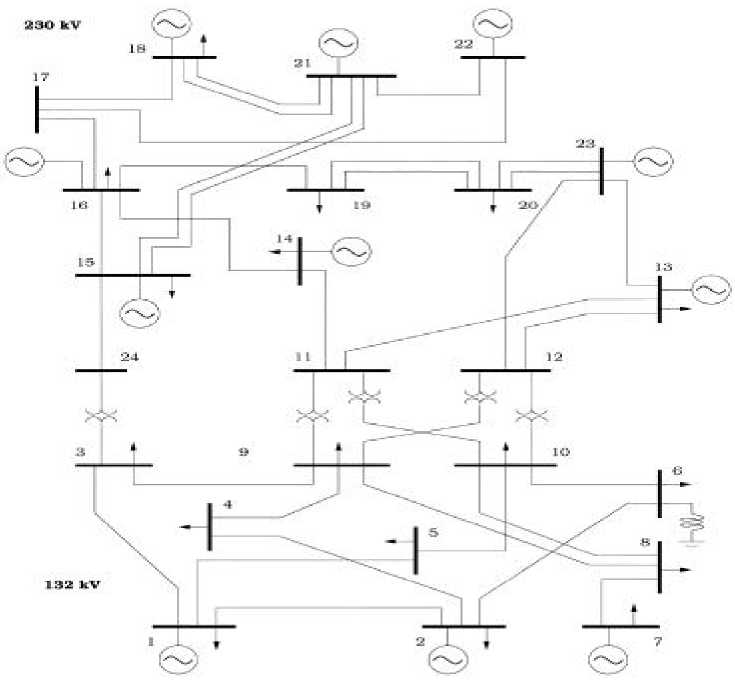

Figure 3: IEEE 24 buses system

To consider wind power plants in the network, two wind farms are situated in buses 15 and 18 that the installed capacity of each of them to simulate different scenarios for wind power penetration coefficient, differs from zero to 800vmega watts. Also figure (4) shows the average power value on producible unit of each of the farms during 24 hours.

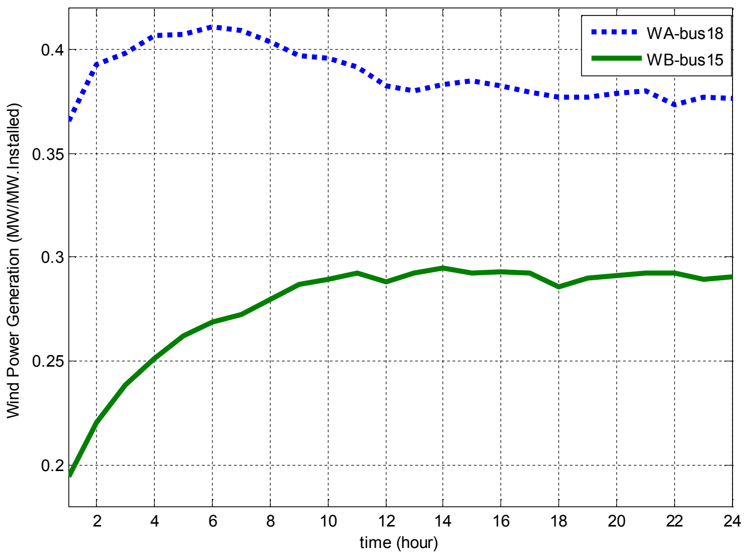

Figure 4: average power production of wind farms

As it is clear in figure 5, marginal cost will decrease after wind power plants penetration coefficient to be increased. In this figure, marginal cost are drawn in shins 6, 18 and 24.

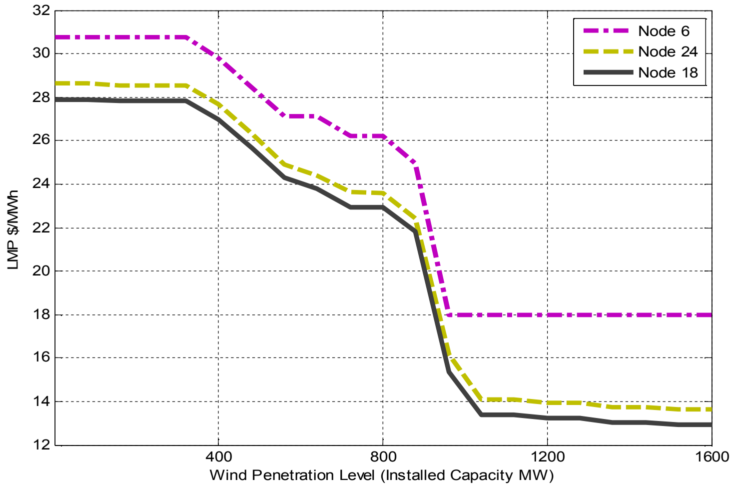

Figure 5: Marginal cost on 18th hour of the day at operation Period

To cover the wind uncertainty adequately, 5000 scenarios of wind potency has been produced and using SCENRED tool in GAMS software, they have decreased to 10 scenarios. All the models have been optimized in GAMS software and by Cplex.12 solver.

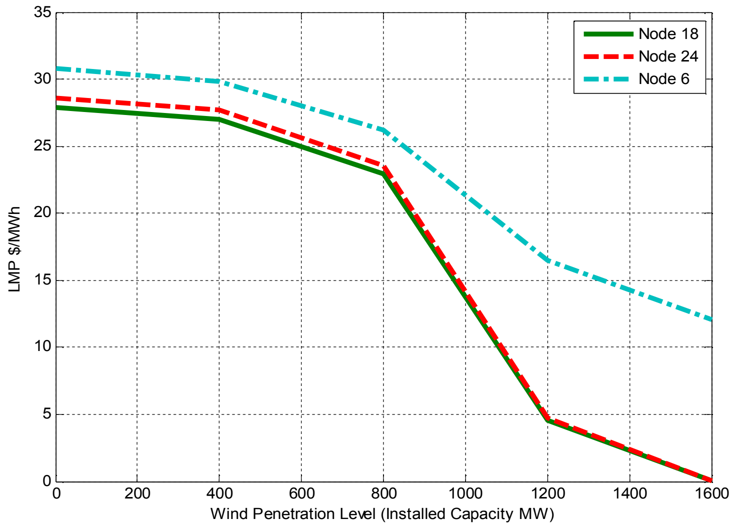

Figure 6: Marginal cost with Considering uncertainty , 18th hour of the day

The considerable difference in this section compared to operation without considering uncertainty of wind units is the effect of the increase in penetration coefficient on dramatic decrease in marginal cost in different shins. Qua even in wind farm shins and the nearby shines the marginal cost reach zero. In operating regarding uncertainty, the model is encountered with a group of wind power production scenarios which bear lots of differences with each other and are different in shape. While finally solving the model must lead to an answer with which the system stability would be guaranteed against all the wind power scenarios.
Figure (7) shows the marginal cost in two types of operation with and without considering uncertainty in producing wind power plants.

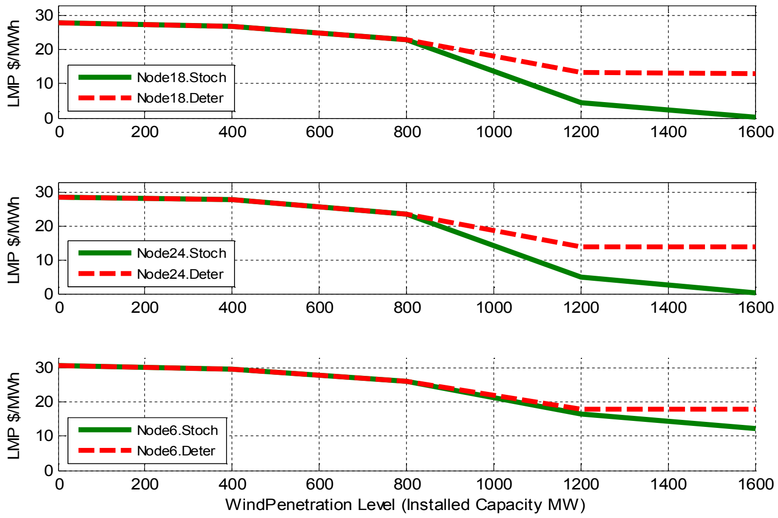

Figure 7: marginal cost in two types of certain and uncertain operation

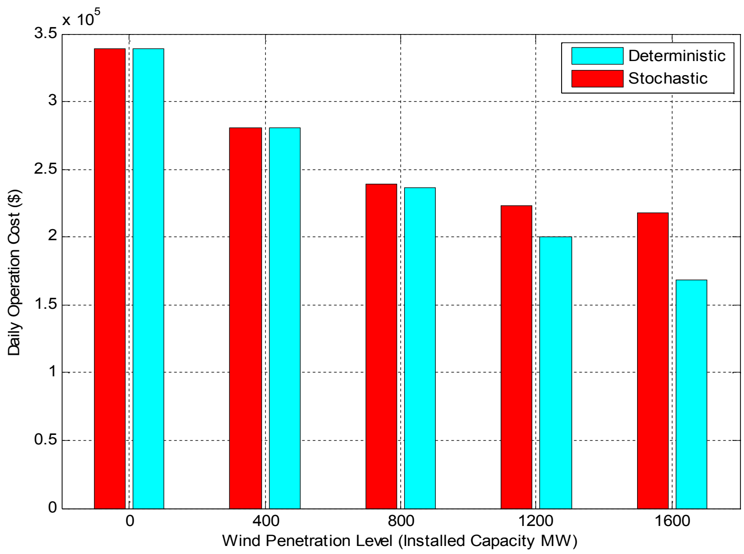

Figure 8: cost of daily operation with and without considering wind uncertainty

CONCLUSION

In this paper, modeling and surveying the use of wind power production in operating the other day of a network in condition of power production uncertainty of wind plants, was studied. Operating the system considering high penetration of wind plants (uncertainty in wind plants output) was solved by unit commitment program and the impact of using wind power and increasing their penetration coefficient on marginal cost was discussed. For this purpose, influences of using wind power on the system was calculated and the way of producing wind power scenarios to use in plants commitment program regarding uncertainty was presented modeling the operation in this environment considering uncertainty in wind plants power production was evaluated.

The general result of this paper is the considerable impact of wind units on power system operation. In this way that:

1. By increasing penetration coefficient of wind power in the system, marginal cost mostly decrease in all the buses and also the cost of operation will reduc
2. The operation cost for one state from the installed capacity values of wind power which means 400 mega watts for both types of operation will be the same and in the other installed capacity, operation cost considering uncertainty will be more

3. Because of the buses near wind farms to present more wind power, marginal cost will reduce more in these buses.
4. Considering uncertainty of wind units power production, because of power fluctuations in different scenarios, using reforming measures to guarantee network stability and keeping the balance, is unavoidable and as a consequence operation cost will increase in proportion to the increase in uncertainty. This operation gives us more comprehensive and real vision towards system costs and the way to face accidental parameters of the system.

According to the studies done in this paper in the field of operating considering uncertainties available in wind plants power production, the following suggestions can be made for more studies and presenting more comprehensive models:

1. Considering uncertainty in other system operation parameters such as price and predicted load
2. Considering the relationship between wind farms according to wind blow speed and adding that to the wind scenario production trend
3. Considering demand respond as the virtual producer and studying its influence on power systems operation
4. Multi-targeted modeling considering target functions at the same time such as energy provide cost and minimizing the curve deviation of daily charge from its average amount.

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