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# Wind-thermal Dispatch Strategy Considering Curtailment Cost of Wind Power

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**Abstract:** In view of frequent wind-curtailed phenomenon in the power generation process, this study constructs a power generation scheduling model which considers the curtailment cost of wind power. In the objective function, When the wind power is curtailed, the total power generation costs will be increased as the punishment mechanism of wind power curtailment. At the same time, the utilization ratio limit of wind power will also be taken into consideration for the constraint conditions. Through the Lagrange function, we can deduce the calculation formula of the curtailment cost of wind power. The numerical example shows that, compared with the traditional scheduling strategy, this new strategy which considers the curtailment cost of wind power, would effectively increase the utilization rate of wind power and reduce the output of the thermal power generation.

**Key words:** Power dispatch, the curtailment cost of wind power, punishment mechanism, wind power utilization

## INTRODUCTION

Wind power generation is different from other traditional forms of electricity generation for its generation power depends on the wind speed, so it has a certain degree of randomness and intermittent. From the efficient utilization of new energy's point of view, the wind power generation should be used as far as possible. However, due to the shortage of the power grid acceptance capacity, the mismatch of the wind energy construction period and the instability of the wind power, it is not possible to make full use of wind power resources. Grid scheduling also has reservations about the use of wind power because of the wind power prediction error and its output volatility. These conditions make the wind power utilization restricted.

As the wind power construction quantity and scale increased, the power grid's utilization rate of the wind power has not been improved accordingly and the power grid has different degrees' wind-curtailed phenomena all over the world. In 2011, the northeastern, northern and northwestern China abandoned wind power of 12.3 billion kilowatt hour with the abandon wind rate amounted to 16% while the rate in Gansu and Meng Dong area are more than 25% (CESC, 2012). In 2009, the Texas ERCOT in the United States daily disposed wind 0.1-2 GWh on average with the maximal rate of 3.9 GWh while the amount of the abandoned wind power reached 16% of the total wind power generation for the whole year. From the year 2004 to 2006, Germany's total abandoned-wind power was amounted to 74 GWH (Fink *et al*., 2009).

Currently, the considering wind power electricity system scheduling research includes the wind power prediction (Bhaskar and Singh, 2012.; Bludszuweit *et al*., 2008), the operating reserve optimization (Liu and Tomsovic, 2012; Lee *et al*., 2007; Morales *et al*., 2009), optimal power flow (Shi *et al*., 2012; Jabr and Pal, 2009), the economic dispatch (Hetzer *et al*., 2008; Farhat and El-Hawary, 2010), the unit commitment (Ummels *et al*., 2007; Methaprayoon *et al*., 2007) and so on. There are no special researches on power dispatch considering wind power curtailment.

From the view of the operation stability, the grid scheduling subjectively tend to use more thermal power units to control the wind power generation scale which has a strong volatility. So how to coordinate the relation between the wind power's acceptance ability and the use of wind power and how to measure the utilization level of the wind power grid are the key problems while considering the scheduling of the wind power grid. If curtailment cost of wind power can be increased in the scheduling objective, then the arbitrarily wind power curtailment could be effectively inhibited from the running cost in dispatching departments.

This study puts forward the grid scheduling model which considers the cost of wind power curtailment and deduces its calculation to encourage the fullest possible use of wind power for grid dispatching and intend to explore the new wind-thermal power dispatch.

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## MATHMATICAL MODEL

Due to the renewable nature of wind resources, the cost of wind power has often been neglected. The wind farm grid scheduling model still takes the lowest thermal power cost as its objective function. The conventional scheduling policy's objective function is:

$$\min\sum_{i=1}^{N}(a_iP_i^2+b_iP_i+c_i) \quad (1)$$

Let the available wind power $P_w^{avail}$ in each period be a known variable that can be predicted; while wind power curtailment $P_w^{curtail}$ is decided by scheduling as a decision variable. If the objective function only considers the thermal power cost, wind power curtailment is not directly subject to constraints and cannot guarantee the minimum. This paper considers punishment price of wind power curtailment$\rho_w$ and multiplies it with the abandoned wind volume as the cost of the abandoned wind punishment to include it into the objective function. The objective function is as follows:

$$\min\{(\sum_{i=1}^{N}(a_iP_i^2+b_iP_i+c_i)+\rho_w^c P_w^{curtail} \quad (2)$$

And the minimum utilization of wind power is considered in the constraint conditions as follows:

$$\frac{P_w^{avial}-P_w^{curtail}}{P_w^{avial}}\times 100\% \geq \eta_w \quad (3)$$

If there are a number of wind farms distributed in different nodes in the system, then we can use the wind power $P_w^{avail}$ and the abandoned wind power $P_w^{curtail}$ as the sum of the output in all wind farms and the abandoned wind power:

$$P_w^a=\sum_{i=1}^{Nw}P_{wi}^a \quad (4)$$

$$P_w^c=\sum_{i=1}^{Nw}P_{wi}^c \quad (5)$$

Let the vector:

$$P_w^c=(P_{w1}^{curtail},P_{w2}^{curtail},\ldots P_{wn}^{curtail})$$

$$P_w^a=(P_{w1}^{avail},P_{w2}^{avail},\ldots P_{wn}^{avail})$$

then:

$$P_w^{avail}=\sum_{i=1}^{wn}P_{wl}^{avail}=(P_w^{a\,T}.P_w^a)^{\frac{1}{2}} \quad (6)$$

$$P_w^{curtail}=\sum_{i=1}^{wn}P_{wi}^{curtaill}=(P_{wi}^{c\,T}.P_w^c)^{\frac{1}{2}} \quad (7)$$

In which, $P_w^{aT}-P_w^a$'s transposed vector $(P_w^a)^{\frac{1}{2}}$- represents vectors that compose of $P_w^c$'s each element's square root, as follows:

$$(P_w^a)^{\frac{1}{2}}=(\sqrt{P_{w1}^{avail}},\sqrt{P_{w2}^{avail}},\ldots,\sqrt{P_{wn}^{avail}}) \quad (8)$$

In a similar way: $P_w^{cT}-P_w^c$'s transposed vector $(P_w^c)^{\frac{1}{2}}$- represents vectors that compose of $P_w^c$'s each element's square root.

The scheduling model (vector form) which considers the abandoned-wind punishment cost is as follows:

$$\min(P^T\Lambda P+P^Tb+c+\rho_w(P_w^{cT})^{\frac{1}{2}}(P_w^c)^{\frac{1}{2}}) \quad (9)$$

$$\text{s.t. } B\theta=P-P_D+(P_w^a-P_w^c) \quad (10)$$

$$P^{min}\leq P\leq P^{max} \quad (11)$$

$$|X^{-1}H\theta|\leq F^{max} \quad (12)$$

$$R\leq R^{max} \quad (13)$$

$$P+R\leq P^{max} \quad (14)$$

$$\frac{(P_w^{aT})^{\frac{1}{2}}(P_w^a)^{\frac{1}{2}}-(P_w^{cT})^{\frac{1}{2}}(P_w^c)^{\frac{1}{2}}}{(P_w^{aT})^{\frac{1}{2}}(P_w^a)^{\frac{1}{2}}}\times 100\% \geq \eta_w \quad (15)$$

$P$ = Thermal power units output
$P_D$ = System load
$R$ = Each unit's spare capacity
$R_{max}$ = Each unit's largest spare capacity
$F_{max}$ = Line trend restrictions
$\Lambda$ = The diagonal matrix that takes the second-order coefficient of the power generation's cost function as the pivot element
$b$ = Vector composes of the power generation cost's first-order coefficient function
$c$ = Vector composes of the power generation cost's zero-order coefficient
$B$ = System electrical susceptance matrix
$\theta$ = Voltage amplitude vector in all nodes of the system ($\theta_{ref}=0$)
$X$ = System's electrical reactance matrix
$H$ = Node and the line's connection matrix, shows as:

$$H_{N\times L}=\begin{cases}1 & \text{Line's starting node}\\ -1 & \text{Line's ending node}\\ 0 & \text{Non-line node}\end{cases}$$

N represents the number of nodes, Lrepresents the number of lines.

## CURTAILMENT COST OF WIND POWER

The mathematical model puts forward by this paper considers the abandoned-wind's cost in the objective function and multiplies it with the volume of the abandoned wind power, thus obtains the abandoned-wind's punishment cost for the purpose of the effective restriction of abandoning winds at will. As the value measure of the abandoned wind behavior, the wind power curtailment price is the quantitative identification that measures whether the abandoned-wind power is reasonable and plays a key role in consciously inhibiting abandoning wind power. Through the KKT conditions in this paper's mathematical model, we can derive curtailment price of wind power as follows:

$$\begin{aligned} L &= P^T \Lambda P + P^T b + \rho_w (P_w^{cT})^{\frac{1}{2}} (P_w^c) \frac{1}{2} \\ &-\mu (B\theta - P + P_D - (P_w^a - P_w^c)) \\ &-v^-(P^{min} - P) + v^+(P^{max} - P) \\ &+\varepsilon^+(F^{max} - X^{-1} H\theta) - \varepsilon^-(F^{min} - X^{-1} H\theta) \\ &+\lambda(\eta_w - \frac{(P_w^{aT})^{\frac{1}{2}}(P_w^a)^{\frac{1}{2}} - (P_w^{cT})^{\frac{1}{2}}(P_w^c)^{\frac{1}{2}}}{(P_w^{aT})^{\frac{1}{2}}(P_w^a)^{\frac{1}{2}}}) \end{aligned} \tag{16}$$

$$\frac{\partial L}{\partial P} = 2\Lambda P + b + \mu + v^- - V^+ - \xi^+ = 0 \tag{17}$$

$$\begin{aligned} \frac{\partial L}{\partial P} &= \rho_w \bullet \frac{1}{2}(P_w^{cT})^{-\frac{1}{2}} \bullet \frac{1}{2}(P_w^c)^{-\frac{1}{2}} \\ &-e^T\mu + \lambda^-(P_w^{aT} \bullet (P_w^a).^{-\frac{1}{2}} \bullet \frac{1}{2}(P_w^{cT})^{-\frac{1}{2}} \bullet \frac{1}{2}(P_w^c)^{-\frac{1}{2}} \\ &= -e^T\mu + \frac{1}{4}(P_w^{cT} \bullet P_w^c)^{-\frac{1}{2}} \bullet (\rho_w + \lambda(P_w^{aT} \bullet (P_w^a)^{-\frac{1}{2}}) \\ &= 0 \end{aligned} \tag{18}$$

$$\frac{\partial L}{\partial \theta} = -\mu b - \varepsilon^+ X^{-1} H + \varepsilon^- X^{-1} H = 0 \tag{19}$$

$$\frac{\partial L}{\partial \mu} = B\theta - P + P_D - (P_w^a - P_w^c) = 0 \tag{20}$$

$$\frac{\partial L}{\partial v^-} = P - P^{min} = 0 \tag{21}$$

$$\frac{\partial L}{\partial v^+} = P^{max} - P = 0 \tag{22}$$

$$\frac{\partial L}{\partial \varepsilon^+} = F^{max} - X^{-1} H\theta = 0 \tag{23}$$

$$\frac{\partial L}{\partial \varepsilon^-} = X^{-1} H\theta - F^{min} = 0 \tag{24}$$

$$\frac{\partial L}{\partial \eta^+} = R^{max} - R = 0 \tag{25}$$

$$\frac{\partial L}{\partial \varsigma^+} = P^{max} - P - R = 0 \tag{26}$$

$$\frac{\partial L}{\partial \lambda} = \eta_w - \frac{(P_w^{aT})^{\frac{1}{2}}(P_w^a)^{\frac{1}{2}} - (P_w^{cT})^{\frac{1}{2}}(P_w^c)^{\frac{1}{2}}}{(P_w^{aT})^{\frac{1}{2}}(P_w^a)^{\frac{1}{2}}} = 0 \tag{27}$$

$$v^- (P^{min}\text{-}P) = 0 \tag{28}$$

$$v^+(P^{max}\text{-}P) = 0 \tag{29}$$

$$\varepsilon^+(F^{max}\text{-}X^{-1}H\theta) = 0 \tag{30}$$

$$\varepsilon^- (F^{min}\text{-}X^{-1}H\theta) = 0 \tag{31}$$

$$\eta^+(R^{max}\text{-}R) = 0 \tag{32}$$

$$\varsigma^+(P^{max}\text{-}P\text{-}R) = 0 \tag{33}$$

$$\lambda(\eta_w - \frac{(P_w^{aT})^{\frac{1}{2}}(P_w^a)^{\frac{1}{2}} - (P_w^{cT})^{\frac{1}{2}}(P_w^c)^{\frac{1}{2}}}{(P_w^{aT})^{\frac{1}{2}}(P_w^a)^{\frac{1}{2}}} = 0 \tag{34}$$

Through the above formulas, we can deduce:

$$\rho_w = 4e^T \mu P_w^{curtail} - \frac{\lambda}{P_w^{curtail}} \tag{35}$$

In the above formula, the physical meaning of Lagrange multipliers corresponding to the constraints (10) is the node price, the physical meaning of Lagrange multipliers corresponding to the constraints (15) is the increased marginal cost of power generation due to the lack of wind power utilization.

From the Eq. 35,we can see that the cost of the abandoned wind is relevant to the available wind power, the abandoned-wind power and the node electricity price. Analyzing Eq. 35, we can get their relations as follows:

- Under the same available wind power ($P_w^{avail}$) conditions, the larger the abandoned-wind power ($P_w^{curtail}$) is, the higher the punishment cost will have. This is consistent with the practical physical meaning. To further analyze, if the wind-power utilization rate cannot meet the minimum requirement of the wind power utilization $\eta_w$, the further it deviates from $\eta_w$, the larger the Lagrange multiplier $\lambda$ corresponding to the constraints (15) will be, that is to say, because the increased marginal price of the power generation's cost due to the lack of wind power generation's utilization is higher, then the abandoned wind price will be further increased

- Under the same available wind power ($P_w^{avail}$) conditions, the higher the node price μ is, the higher the abandoned-wind cost $\rho_w$ it obtains. The physical meaning of the node's electricity price is the increase of the power generation's cost caused by the increased unit's load in the system. The high node price means the system's marginal cost of power generation is high, then arbitrarily abandoning wind behavior will pay a higher price, quantified as the high price of the abandoned wind

## SIMULATION CASE

This study makes the simulation of IEEE-30 node system. Let the wind speed be consistent with Weibull distribution, parameters are: k = 2.15, c = 8.30. Assume that the wind power grid node is node 11, conventional unit 1 is the balance unit, the other five conventional units' active power output are variables to be optimized.

The system's forecasted load and the forecasted wind power output are shown in Fig. 1.

Results of the traditional schedule and proposed scheduling considering the wind power curtailment cost are shown in Fig. 2.

In Fig. 2, Series1 indicates the planned wind power outputs of each period (conventional scheduling strategy); Series 2 indicates the planned wind power outputs of each time (scheduling strategy considering the abandoned-wind cost); Series3 indicates the available wind power of each period.

The total available wind power of 24 periods is 794 MW, the total output of the conventional scheduling strategy's planned wind power is 620 MW, the total output of the planned strategy that considering the cost of the abandoned wind power is 723 MW. The wind power's utilization rate of the conventional scheduling strategy is 80.6045% and the wind power's utilization rate of the conventional scheduling strategy that considering the abandoned wind cost is 91.0579%.

In Fig. 3, Series 1 indicates the generation cost of the conventional scheduling strategy; Series 2 indicates the cost of the scheduling policy's power generation considering the abandoned wind cost. The total power generation cost of the conventional scheduling policy is 60,477,850 CNY, the cost of the scheduling strategy's thermal power generation considering the abandoned wind cost is 59,283,650 CNY, the abandoned wind cost is 133,424 CNY and the total cost is 59,417,074 CNY.

Figure 4 shows curtailment cost of wind power for 24 periods. In the periods that all used by the wind power (3, 10, 11, 12, 13, 14, 15), the wind power is zero, namely the curtailment cost is zero, so curtailment price does not make any sense, set it as zero. The highest price of the abandoned wind period is 17, this period has a heavy load while the available wind power is low, so that makes curtailment cost relatively high. That is to say, the abandoned wind in this

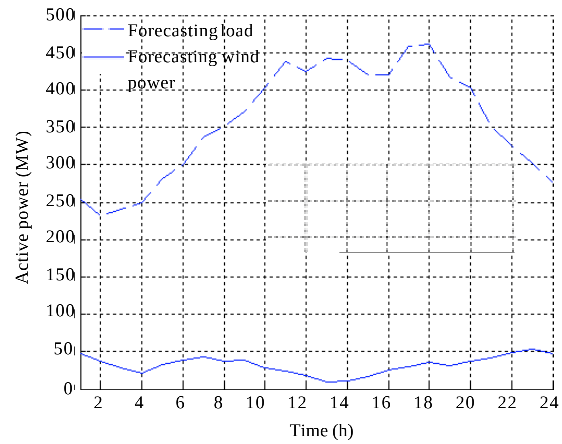


Fig. 1: Curves of load and wind power forecast

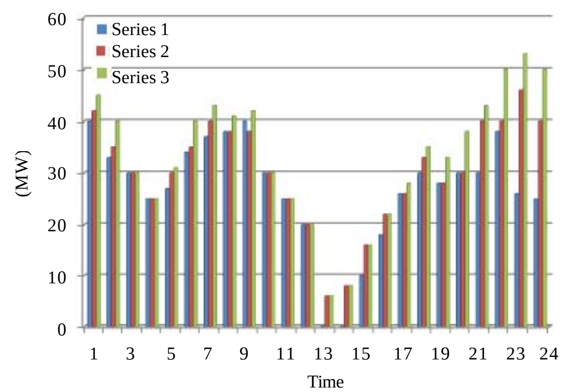


Fig. 2: Wind power planning output and the available wind power

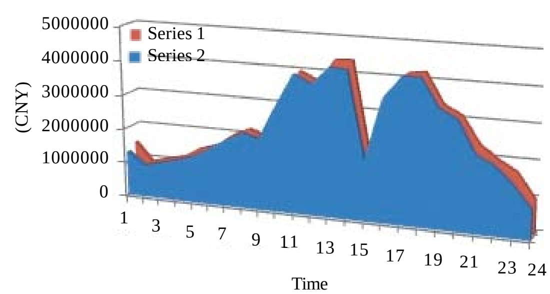


Fig. 3: Costs of power generation in different strategies

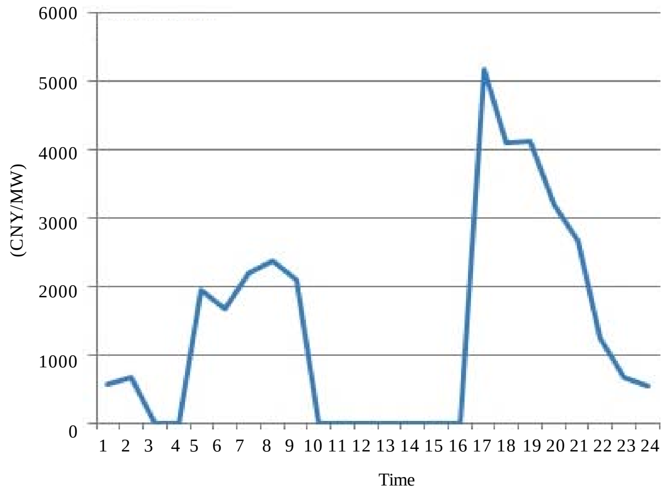


Fig. 4: Curtailment cost of wind power

period of time will pay higher cost as punishment. The periods with a higher curtailment cost include 5-9, 18-20.

## CONCLUSION

This study puts forward a new model considering curtailment cost of wind power as punishment. The calculation formulae of the curtailment cost deduced through the Lagrange function which indicates that curtailment cost of wind power relative to the available wind power, the abandoned-wind power and location marginal price. Under the same available wind power conditions, the larger the abandoned wind power, the higher the punishment cost. Meanwhile, the higher location marginal price, the higher the punishment cost. The simulation results prove that new schedule model can increase the utilization rate of the wind power effectively and save the cost of thermal power generation.

## REFERENCES

Bhaskar, K. and S.N. Singh, 2012. AWNN-assisted wind power forecasting using feed-forward neural network. IEEE Trans. Sustain. Energy, 3: 306-315.

Bludszuweit, H., J.A. Dominguez-Navarro and A. Llombart, 2008. Statistical analysis of wind power forecast error. IEEE Trans. Power Syst., 23: 983-991.

CESC, 2012. Wind power consumptive regulatory report in key regions. China Electricity Supervise Committee, Beijing, China.

Farhat, I.A. and M.E. El-Hawary, 2010. Dynamic adaptive bacterial foraging algorithm for optimum economic dispatch with valve-point effects and wind power. IET Generation Transmission Distrib., 4: 989-999.

Fink, S., C. Mudd, K. Porter and B. Morgenstern, 2009. Wind energy curtailment case studies May 2008-May 2009. Subcontract Report No. NREL/SR-550-46716. http://www.nrel.gov/docs/fy10osti/46716.pdf.

Hetzer, J., D.C. Yu and K. Bhattarai, 2008. An economic dispatch model incorporating wind power. IEEE Trans. Energy Convers., 23: 603-611.

Jabr, R.A. and B.C. Pal, 2009. Intermittent wind generation in optimal power flow dispatching. IET Generation Transmission Distrib., 3: 66-74.

Lee, T.Y., 2007. Optimal spinning reserve for a wind-thermal power system using EIPSO. IEEE Trans. Power Syst., 22: 1612-1621.

Liu, G. and K. Tomsovic, 2012. Quantifying spinning reserve in systems with significant wind power penetration. IEEE Trans. Power Syst., 27: 2385-2393.

Methaprayoon, K., C. Yingvivatanapong, W.J. Lee and J.R. Liao, 2007. An integration of ANN wind power estimation into unit commitment considering the forecasting uncertainty. IEEE Trans. Ind. Appl., 43: 1441-1448.

Morales, J.M., A.J. Conejo and J. Perez-Ruiz, 2009. Economic valuation of reserves in power systems with high penetration of wind power. IEEE Trans. Power Syst., 24: 900-910.

Shi, L., C. Wang, L. Yao, Y. Ni and M. Bazargan, 2012. Optimal power flow solution incorporating wind power. IEEE Syst. J., 6: 233-241.

Ummels, B.C., M. Gibescu, E. Pelgrum, W.L. Kling and A.J. Brand, 2007. Impacts of wind power on thermal generation unit commitment and dispatch. IEEE Trans. Energy Convers., 22: 44-51.