An Early Warning Method Based on Improved Affine Arithmetic for Wind Power Ramp Events in Power System

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Abstract. With more and more wind power integrated into power system, increasing attention is paid to wind power ramp events (WPREs) due to the significant impact on the power balance of power system. Considering the impact of large volatility of WPREs on power control, the permissible intervals of ramping amplitude are analysed to determine the boundaries between different warning stages, which are corresponding to different power control measures to keep the power balance with Area Control Error (ACE) deviation maintained within the allowable range. Moreover, interval analysis is introduced to deal with the strong uncertainty, and an improved affine arithmetic is proposed to deal with the conservation brought by interval analysis by considering the temporal correlation of WPREs prediction error. A multi-stage early warning method for WPREs is established in further, by which the warning information, including boundaries and probability distributions, can be provided reflecting the degree of potential harm inflicted by WPREs. Simulation results demonstrate that, the provided warning information have clear physical meanings to provide guidance for the operators, and the proposed warning method has simple and rapid characteristics, which reflects the verify the effectiveness of the proposed method.

1. Introduction

In recent years, large-scaled wind power is integrated into power system world-wide. However, the inherent volatility and uncertainty of wind power bring great challenge to power system operation. With increasing penetration rate of wind power generation, wind power ramp events (WPREs) [1] with great ramp rates may lead to more economical loss and less system stability. Therefore, it is necessary to provide applicable tools for classifying, predicting, warning, and controlling of WPREs. The strong volatility is one of the main characters of WPREs [2], at scenario of the high wind power penetration, the direct impact of ramp events is the power imbalance, the capacity and regulation ability of power control measures determine the corresponding warning threshold of WPREs. In addition, the strong uncertainty of wind power ramp prediction exacerbates the power imbalance problem [3]. Currently, preliminary studies have been carried out in the area of definition [4], characteristics statistical analysis [5] and prediction [6] on WPREs, but there have been no researches reported on perception and control.
of WPREs. Therefore, it has an urgent necessary and theoretical value to seek an early warning method [7] for WPREs.

The determination of the thresholds of warning indicators is the key to the early warning system. Several mathematical definitions of WPREs are proposed in [5], in which a wind power ramp event is considered to occur when the amplitude or ramp rate of wind power ramp exceeds the corresponding threshold. In many countries, technical regulations for connecting wind farm to grid [8] containing the restrictions upon the change rate of wind power output have been proposed to prevent or reduce the adverse effects of wind farm on power grid. All these researches can be regarded as providing warning thresholds for WPREs. However, in actual operation of power system, the reserve capacity, units output, load capacity and other operation status vary all the time, even the unit commitment status and grid structure may also change. Different power systems or the same power system at different times have different tolerances to WPREs, therefore the corresponding warning thresholds should also be different, making judgment with uniform warning thresholds is not appropriate, and it is necessary to analysis the impact of WPREs for the operation status of power system and provide warning information based on the analysis results.

This paper is organized as follows: Section 2 proposes an improved affine arithmetic consider correlation of WPREs prediction errors. Section 3 presents the calculation method for permissible range of wind power ramp and the early warning method based on the permissible interval of wind power ramp amplitude. Section 4 verify the effectiveness of the proposed early warning method by simulation cases. Section 5 concludes the paper.

2. Improved affine arithmetic considering temporal correlation of prediction error

The prediction error of wind power is the difference between the actual and predicted value of wind power, the relationship among these three variables can be expressed as follow:

\[ P_{\text{wind}}(t) = \tilde{P}_{\text{wind}}(t) + \varepsilon_t \]  

Where \( P_{\text{wind}}(t) \) is the actual value of wind power at time \( t \); \( \tilde{P}_{\text{wind}}(t) \) is the predicted value of wind power at time \( t \), which is provided by wind power forecasting system in advance; \( \varepsilon_t \) is the prediction error of wind power at time \( t \).

The prediction errors with temporal correlation can be decomposed into two affine elements [9]: one is a common element to reflect the same impact infect for prediction errors at different times, the other is independent element reflecting different impact infects. The affine distribution model is shown as follows:

\[ \varepsilon_t = a_t \xi_0 + b_t \xi_t \]  

Where \( \xi_0 \) and \( \xi_t \) are two standard normal distributions independent with each other; \( a_t \) and \( b_t \) are corresponding coefficients that make \( \varepsilon_t \) subject to their corresponding probability distributions respectively.

Assume that the confidence interval of wind power prediction, \( [P_{\text{wind}}(t), P_{\text{wind}}(t)] \) with confidence level \( \alpha \), is provided by WPRE prediction system. The confidence interval of prediction error \( \varepsilon_t \) can be expressed as follow:

\[ [-z_{\alpha}(\sigma), z_{\alpha}(\sigma)] = [P_{\text{wind}} - \tilde{P}_{\text{wind}}, P_{\text{wind}} - \tilde{P}_{\text{wind}}] \]
Based on the relationship among prediction error $\varepsilon_t$ and its affine elements as shown in equation (2), a confidence level, represented as $\lambda$, of intervals of affine elements is desired to satisfy the algorithm of interval analysis, which can be expressed as follow:

$$[-z_{a}(\sigma), z_{a}(\sigma)]=[-z_{\lambda}(a), z_{\lambda}(a)] + [-z_{\lambda}(b), z_{\lambda}(b)]$$

(4)

When confidence level $\theta$ is given, the ratio of $z_{\theta}(\sigma)$ to standard deviation $\sigma$ is fixed, for example, $z_{68.26%}(\sigma)=\sigma$, $z_{95.44%}(\sigma)=2\sigma$, $z_{90%}(\sigma)=1.6447\sigma$. Therefore, we can assume that:

$$z_{\theta}(\sigma) = m\sigma$$

(5)

$$z_{\rho}(\sigma) = n\sigma$$

(6)

It is easy to get the following equation considering (6):

$$m\sigma = n(a + b)$$

(7)

Therefore, values of $\lambda$ and $n$ can be obtained as follow:

$$n = \frac{m}{\sqrt{\rho(e_1, e_2)} + \sqrt{1 - \rho(e_1, e_2)}}$$

(8)

$$\lambda = 2\int_{0}^{\mu} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{x^2}{2\sigma^2}} dt$$

(9)

### 3. Calculation method for permissible range of wind power ramp

It is one of the main responsibilities for power system operators to achieve power balance and limit Area Control Error (ACE) in allowable range. In this situation, conventional generators are the major measures to regulate power balance with primary frequency regulation, secondary frequency regulation, and economic dispatch. ACE deviation can be used as clues to analysis the power balance status and calculate corresponding boundaries of allowed ramp intervals. Specific analysis corresponding to different control measures are shown as follow:

#### 3.1. Permissible range with automatic power balance control

Automatic power balance control includes primary frequency regulation and secondary frequency regulation (AGC). Primary frequency regulation includes automatic control of speed governing system for conventional units and load response to frequency deviation for demand side. In case primary frequency regulation is insufficient to stabilize the frequency within the allowable range, it is necessary to activate the secondary frequency regulation to adjust the output of in-service conventional units. In this situation, it is satisfied that for every $\Delta P_{wr}(t)$ belongs to $\left[\frac{\Delta P_{wr - p}(t)}{\Delta P_{wr - p}(t)}\right]$, there exists a $\Delta P_{of}(t)$, which belongs to $[\Delta P_{of, min}(t), \Delta P_{of, max}(t)]$, making it possible to achieve power balance with controlled ACE within $[ACE_{min}, ACE_{max}]$.

$$P_{w0}(t) + e(t) + \sum_{i=1}^{N_h} P_{G_i}(t) - \sum_{i=1}^{N_h} \frac{1}{R_i} \Delta f(t) = P_i(t) + D\Delta f(t) + \Delta P_{ne}$$

(10)
where $\Delta P_{wr}(t)$ is the amplitude of wind power ramp, $\left[ \Delta P_{wr_{-p}}(t), \Delta P_{wr_{+p}}(t) \right]$ is the ramp amplitude interval constituted by ramp boundaries provided by wind power ramp prediction system, $[ACE_{min}, ACE_{max}]$ is the allowable range of ACE value, $N_G$ is the number of conventional units, $R_i$ is the speed regulation of unit $i$, $D$ is the composite load-damping constant, $\Delta P_l$ is the predicted power variation of load, $N_{AGC}$ is the number of AGC units, $\Delta P_{Gi}$ is the regulation quantity of unit $i$.

Equation (10) can be simplified as follow:

$$\Delta P_{wr}(t) = \Delta P(t) + ACE - \sum_{j=1}^{N_{AGC}} \Delta P_{Gi}(t) - \left( \varepsilon(t) - \varepsilon(t_0) \right)$$

(11)

Considering the correlation of wind power prediction errors:

$$\varepsilon(t) - \varepsilon(t_0) = b \left( \xi(t) - \xi(t_0) \right)$$

(12)

Equation (11) can be converted into interval representation to get the wind power permissible range corresponding to power balance status under secondary frequency regulation:

$$\left[ \Delta P_{wr_{1}}(t), \Delta P_{wr_{2}}(t) \right] = \Delta P(t) + \left[ ACE_{min}, ACE_{max} \right] - \sum_{j=1}^{N_{AGC}} \left[ \Delta P_{Gi}^{max}(t), \Delta P_{Gi}^{min}(t) \right] - 2b[-n, n]$$

(13)

It can be got using interval algorithm:

$$\Delta P_{wr_{2}}(t) = \Delta P(t) - \sum_{j=1}^{N_{AGC}} \Delta P_{Gi}^{max}(t) + ACE_{min} + 2nb$$

(14)

$$\Delta P_{wr_{1}}(t) = \Delta P(t) - \sum_{j=1}^{N_{AGC}} \Delta P_{Gi}^{min}(t) + ACE_{max} - 2nb$$

(15)

3.2. Permissible range with spinning reserve

It is assumed that the power balance status can be achieved only by using spinning reserve, scilicet, only by adjusting the power output of generators that are already connected to the power system. In this situation, it is satisfied that for every $\Delta P_{wr}(t)$ belongs to $\left[ \Delta P_{wr_{-p}}(t), \Delta P_{wr_{+p}}(t) \right]$, there exists a $\Delta P_{Gm}(t)$, which belongs to $[\Delta P_{Gm_{-min}}(t), \Delta P_{Gm_{max}}(t)]$, making it possibile to achieve power balance with ACE controlled within $[ACE_{min}, ACE_{max}]$.

$$-\sum_{j=1}^{N_G} \frac{1}{R_j} \Delta f(t) + \sum_{m=1}^{N_{sr}} \Delta P_{m}(t) + \Delta P_{wr}(t) = \Delta P_i(t) + D\Delta f(t) + \Delta P_{tie}$$

(16)

Where $N_{sr}$ is the number of units with spinning reserve, $\Delta P_{Gm}$ is the regulation quantity of unit $m$.

Due to the similarity of adjusting power outputs of online units, the calculation of permissible range under only using spinning reserve has a common ground with the permissible range under secondary frequency regulation. The only difference is that AGC units are regulated automatically, while units
with spinning reserve are adjusted according to scheduling plan. Therefore, the permissible range with only spinning reserve is expressed as follow:

$$\Delta P_{wr2}(t) = \Delta P_1(t) - \sum_{j=1}^{N_G} \Delta P_{G_j}^{max}(t) + ACE_{min} + 2nb$$  (17)

$$\Delta P_{wr2}(t) = \Delta P_1(t) - \sum_{j=1}^{N_G} \Delta P_{G_j}^{min}(t) + ACE_{max} - 2nb$$  (18)

Where $\Delta P_{G_m}^{min}(t)$ and $\Delta P_{G_m}^{max}(t)$ are respectively the minimum and maximum regulation quantity of unit $m$ with spinning reserve at time $t$, which are subjected to constraints of minimum and maximum power output and ramp rate limit of units.

3.3. Permissible range with spinning reserve and non-spinning reserve

Subject to the constraints of capacity and ramp rate limit of spinning reserve, it may not be able to achieve power balance. In this case, non-spinning reserve is required by starting up generators not currently connected to the system (corresponding to ramp-down events) or shutting down online generators (corresponding to ramp-up events). Especially for the wind power ramp-down events, due to the short time scale, the fast-start generators, such as pumped storage power station and gas-turbine units, are preferentially selected to be start up. In this situation, it is satisfied that for every $\Delta P_W(t)$ belongs to the interval $\left[\Delta P_{wr,p}(t), \Delta P_{wr,p}(t)\right]$, there exists a $\Delta P_{G_n}(t)$, which belongs to $[\Delta P_{G_n}^{min}(t), \Delta P_{G_n}^{max}(t)]$, making it a possibility to achieve power balance status with ACE controlled within $[ACE_{min}, ACE_{max}]$.

$$-\sum_{i=1}^{N_G} \frac{1}{R_i} \Delta f(t) + \sum_{m=1}^{N_G} \Delta P_{G_m}(t) + \sum_{n=1}^{N_{nsr}} \Delta P_{G_n}(t) + \Delta P_{wr}(t) = \Delta P_1(t) + D\Delta f(t) + \Delta P_{tie}$$  (19)

Where $N_{nsr}$ is the number of units with non-spinning reserve, $\Delta P_{G_n}$ is the regulation quantity of unit $n$.

Taking the interval transform as interval representation, it can be got that the permissible range of wind power ramp amplitude under using non-spinning and spinning reserves.

$$\left[\Delta P_{wr3}(t), \Delta P_{wr3}(t)\right] = \Delta P_1(t) - \sum_{m=1}^{N_G} \Delta P_{G_m}(t) - \sum_{n=1}^{N_{nsr}} \Delta P_{G_n}(t) + \left[ACE_{min}, ACE_{max}\right] - b[-nb, nb]$$  (20)

Hence, by the interval algorithm

$$\Delta P_{wr3}(t) = \Delta P_1(t) - \sum_{m=1}^{N_G} \Delta P_{G_m}^{max}(t) - \sum_{n=1}^{N_{nsr}} \Delta P_{G_n}^{max}(t) + ACE_{min} + 2nb$$  (21)

$$\Delta P_{wr3}(t) = \Delta P_1(t) - \sum_{m=1}^{N_G} \Delta P_{G_m}^{min}(t) - \sum_{n=1}^{N_{nsr}} \Delta P_{G_n}^{min}(t) + ACE_{max} - 2nb$$  (22)
Where $\Delta P_{G_n}^{\text{min}}(t)$ and $\Delta P_{G_n}^{\text{max}}(t)$ are respectively the minimum and maximum regulation quantity of unit $n$ with non-spinning reserve at time $t$, which are subjected to constraints of minimum start up and shut down time.

$$\Delta P_{G_n}^{\text{max}}(t) = P_{G_n}^{\text{max}} s_u(n, t)$$  \hspace{1cm} (23)

$$s_u(n, t) = \begin{cases} 1, & t - t_0 \geq t_u(n) \\ 0, & t - t_0 < t_u(n) \end{cases}$$  \hspace{1cm} (24)

Where $P_{G_n}^{\text{max}}$ is the maximum allowable active power output of the unit $n$, $s_u(n, t)$ is the identifier representing whether the operation of starting up unit $n$ can be finished at time $t$, $t_u$ is the minimum start up time which depends on the type and state of generator before being start up.

3.4. Permissible range with wind power curtailment or load shedding

If power balance cannot be achieved after taking the measures of spinning and non-spinning reserves, coercive measures including wind power curtailment (corresponding to ramp-up events) and load shedding (corresponding to ramp-down events) have to be used to avoid more serious consequences caused by too high/low ACE. In this situation, the power balance can be described as follow:

$$-\frac{1}{R_i} \sum_{i}^{N_i} \Delta f(t) + \sum_{i}^{N_G} \Delta P_{G_i}(t) + \Delta P_{\text{wind}}^\text{curt}(t) - \Delta P_{\text{wind}}^\text{shed}(t)$$

$$= \Delta P_i(t) - \Delta P_{\text{load}}(t) + D\Delta f(t) + \Delta P_{\text{Tie}}$$  \hspace{1cm} (25)

Where $\Delta P_{\text{wind}}^\text{curt}$ the capacity of wind power curtailment is, $\Delta P_{\text{load}}^\text{shed}$ is the load shedding capacity.

Suppose the installed capacity of wind power is $P_{\text{wind}}^{\text{max}}$, the wind power before ramp event is $P_{\text{wind}}(t_0)$. It is easy to know that, the maximum ramp-up and ramp-down amplitude is $P_{\text{wind}}^{\text{max}} - P_{\text{wind}}(t_0)$ and $-P_{\text{wind}}(t_0)$, respectively. Since the capacity of wind power is always less than total load capacity, thus the power balance can be always achieved by using coercive measures. However, due to the serious adverse impact on the security and reliability of power system, this situation needs to be avoid as far as possible, power control measures mentioned above should be using to balance the active power in power system as soon as possible.

In summary, the boundaries of different warning intervals can be calculated using the method proposed above, by comparing these boundaries with the prediction results of wind power, the multistage early warning for WPRE can be realized, boundaries and probability distributions of different warning stages can be provided to operators.

4. Case studies

A power system with 10 conventional units [10] is used as the test case to verify the method proposed in the paper. The total installed capacity is 2370MW. No. 10 unit with capacity of 455MW, is replaced by a wind farm with the same install capacity. No. 6 unit with capacity of 80MW is regarded as interchange power with neighboring areas, which need to be controlled at scheduled value. It is assumed that all conventional generators take part in primary frequency regulation, No. 1-4 units are AGC units, and the others are regarded as dispatch able units participating in scheduling control. Time interval is 5 min. Load forecasting error is 2%. The allowable range of frequency deviation is ±0.1Hz, allowable
transmission capacity is set as $[0, 2P_{\text{Tie}}]$, i.e. $[0, 160\text{MW}]$. The speed regulations of units are all taken as 5% and the damping constant of load is 1%.

As mentioned in Section III, the correlation coefficients for one hour interval is 0.9. Therefore, the coefficient of affine elements $a \approx 0.9487\sigma$ and $b \approx 0.3162\sigma$. When the confidence level $\alpha$ of interval is set as 90%, the coefficient $m$ is 1.6447, the coefficient $n$ can be obtained as 1.3003, and $\beta$ is 80.65%.

It is assumed that the capacity of load is predicted to increase from 1200MW to 1300MW in the future 1 hour, while a negative WPRE is predicted to occur, the amplitude of wind power ramp is 80% of installed capacity and the duration is 1 hour. The wind power will rapidly decline from 420MW to 56MW, the confidence interval of prediction error with 90% confidence level is $[-53.66\text{MW}, 53.66\text{MW}]$.

According to the multi-stage early warning method proposed in this paper, the permissible intervals of wind power ramp amplitude corresponding to different power control measures can be calculated, which is shown in Figure 1.

![Figure 1. Wind power ramping amplitude and interval boundary curves of different warning stages.](image)

The direction of wind power ramp opposes to that of load variation. In 0~5 minutes, by adjusting the output power of AGC units, the power balance status can be achieved with secondary frequency regulation. After 10 minutes, due to the insufficient capacity of AGC units, the permissible amplitude of wind power ramp-down basically no longer becomes greater because of the impact of load increase. Before 20 minutes, the power balance status can be achieved with only spinning reverse; but after that, due to the limit of rate of regulation, the net load variation caused by wind power ramp-down event and load increase cannot be completely tracked by spinning reserve. In this situation, units with non-spinning reserve cannot be start up and provide extra active power support because of the limit of minimum start-up time, coercive measures, i.e., load shedding, has to be activated to achieve power balance.

Corresponding probabilities of the predicting interval of wind power ramp falling in different warning hierarchies can be calculated, which is shown in Figure 2.
Figure 2. Warning results and probability distributions of intervals of different warning stages

As shown in Figure 2, the cumulative probability of warning is calculated according to the order from low to high stage of early warning. Assume that the risk attitude of operators is to prevent 90% of risk, therefore, the corresponding warning stage when cumulative probability is 90% (expressed as black dashed line in Figure 2) is set to determine the warning stage. In this way, the early warning results at each time are shown as the shading part in the table below Figure 2. Before 5 minutes, the early warning stage is IV; in 10-15 minutes, the early warning stage becomes III; in 20-55 minutes, the warning stage rises to I; at the time of 60 minutes, part of units meet the requirement of the minimum start-up time and can be start up to provide active power support, the warning stage drops to II. Thus there exists the possibility of load shedding in a relatively long period between 20 to 55 minutes, the adverse impact of this wind power ramp-down event on power system is very serious.

5. Conclusion

A multi-stage early warning method for WPREs is proposed. Considering the temporal correlation of WPREs prediction errors, an improved affine arithmetic is proposed to reduce the conservation caused by interval analysis, which is used to deal with the strong uncertainty of WPREs; considering the impact of large volatility of WPRE on power control, the permissible intervals of ramping amplitude corresponding to different power control measures are analyzed to determine the boundaries between different warning stage. By comparing these boundaries with the prediction results of wind power, the multi-stage early warning for WPRE can be realized, boundaries and probability distributions of different warning stages can be provided to operators. Simulation results demonstrate that, the warning information provided by the proposed early warning method has a clear physical meaning, which can instruct operators to take appropriate measures dealing with WPREs.

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