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Coordinated Control Strategy for Power Systems with Wind Farms Integration Based on Phase-plane Trajectory

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Abstract – The dynamic characteristics of power systems become more and more complex because of the integration of large-scale wind power, which needs appropriate control strategy to guarantee stable operation. With wide area measurement system(WAMS) creating conditions for realizing real-time transient stability analysis, a new coordinated control strategy for power system transient stability control based on phase-plane trajectory was proposed. When the outputs of the wind farms change, the proposed control method is capable of selecting optimal generators to balance the deviation of wind power and prevent transient instability. With small disturbance on the base operating point, the coordinated sensitivity of each synchronous generator is obtained. Then the priority matrix can be formed by sorting the coordinated sensitivity in ascending order. Based on the real-time output change of wind farm, coordinated generators can be selected to accomplish the coordinated control with wind farms. The results in New England 10-genrator 39-bus system validate the effectiveness and superiority of the proposed coordinated control strategy.

Keywords: Wind power, Phase-plane trajectory, Transient stability, Coordinated sensitivity, Coordinated control

1. Introduction

With global energy crisis and environmental deterioration, renewable energy sources such as wind power are prioritized over non-renewable sources and subsidized by most of the government organizations [1-2]. Compared with conventional power plants, the intermittency, variability and uncertainty of wind farms make the power system operation more and more complex. Meanwhile, the variable speed constant frequency generators such as double fed induction generators (DFIGs), which are widely used in wind farms, have different dynamic characteristics compared with synchronous generators (SGs). Thus, the large-scale integration of wind farms has brought severe challenges to the transient stability of the power system, which needs appropriate control strategy to guarantee stable operation [3-9].

At present, the control strategies applied for most power systems are developed based on the online/offline simulation with the models and parameters. The effectiveness of the control strategy is subjected to the accuracy of the models and parameters. Since the precise models and parameters cannot be obtained, it might lead to irrational control strategy. With the development of wide area measurement system (WAMS), it's possible to realize real-time transient stability analysis and develop optimal control strategy [10-13].

The method based on phase-plane trajectory can judge transient stability accurately with real-time phase angle and angular velocity measured by WAMS [14-15], indicating a new direction for the transient stability analysis. Up to now, much significant research achievements have been published. It's firstly pointed in [16] that the transient stability of power systems is related to the convexity and concavity of phase-plane trajectory. Based on one machine infinite bus (OMIB) system, the paper [17] strictly proves the relationship between the convexity and concavity of phase-plane trajectory and the transient stability, and proposes an improved instability detection method, which is independent of the network structure, system parameters and model because of using observation data. A transient stability detection method using the trajectory in phase plane obtained by dimension reduction of power angles in power-angle space was proposed in [18], which avoids the coherency identification and greatly saves the computing time. The paper [19] studies the phase-plane trajectory patterns and critical surfaces for second order nonlinear systems with nonsingular terminal sliding mode (NTSM) control. The paper [20] proposes an algorithm for calculating the minimum output cutting of generators based on the slope of phase-plane trajectory and angular velocity.

The aforementioned research mainly focuses on transient stability detection based on phase-plane trajectory. However, there is less research on coordinated control strategy for power systems with wind farms integration. On the basis of

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phase-plane trajectory, this paper proposes a coordinated control strategy: With small disturbance on the basic operating point, the coordinated sensitivity of each synchronous generator is obtained. Then the priority matrix can be formed by sorting the coordinated sensitivity in ascending order. Based on the real-time output deviation of wind farm, coordinated generators can be selected to accomplish the coordinated control with wind farms.

The main advantages of the proposed coordinated control strategy are as follows: (1) It can meet the requirements of both economy and security to balance the deviation of wind power and maintain transient stability for power systems with wind farms integration; (2) The contained transient stability constraint based on phase-plane trajectory has favorable linear characteristics and obvious transient margin compared with rotor angle criterion. (3) Because the threshold of function f is 0, the proposed constraint avoids heuristically selecting thresholds for the maximum relative rotor angle deviation. Therefore, it has great potential for online transient stability control in future application.

In the following section, this paper is organized as follows: Section 2 introduces the transient stability criteria for OMIB system and multi-machine system and the definition of phase-plane trajectory sensitivity. The coordinated control strategy for power system with wind farms integration is described in Section 3. Section 4 provides the application to New England l0-generator 39-bus system. Conclusions are summarized in Section 5.

2. Phase-plane Trajectory Method

2.1 Transient stability criterion based on phase-plane trajectory

Ignoring damping factor, dynamic equation of OMIB system can be denoted as:

$$\begin{cases} \dot{\delta}=\omega \\ \dot{\omega}=\dfrac{1}{M}(P_m-P_{e\max}\sin\delta) \end{cases} \tag{1}$$

where δ is the generator angle and ω is the angular velocity; M is the inertia time constant; P_m is the mechanical input of the generator; P_{emax} is the maximum electric power of the generator.

Phase-plane trajectory with different fault-clearing time is shown in Fig. 1.

The derivation of phase-plane trajectory is written as:

$$k_1=\frac{d\omega}{d\delta}=\frac{(P_m-P_{e\max}\sin\delta)/M}{\omega} \tag{2}$$

The two-order derivation of phase-plane trajectory is written as:

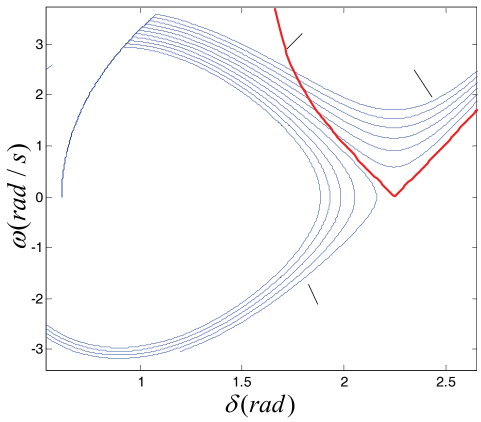

Fig. 1. Phase-plane trajectory with different fault-clearing time

$$k_2=\frac{dk_1}{d\delta}=-\frac{MP_{e\max}\omega^2\cos\delta+(P_m-P_{e\max}\sin\delta)^2}{\omega^3M^2} \tag{3}$$

Suppose k_2=0 then expression (3) is derived as:

$$-(MP_{e\max}\omega^2\cos\delta+(P_m-P_{e\max}\sin\delta)^2)=0 \tag{4}$$

Phase-plane trajectory function $f(\delta,\omega,P_m)$ is defined as:

$$f(\delta,\omega,P_m)=-(MP_{e\max}\omega^2\cos\delta+(P_m-P_{e\max}\sin\delta)^2) \tag{5}$$

As shown in Fig. 1, the phase plane is divided into two areas by a clear curve ($f(\delta,\ \omega,\ P_m)=0$), which is named as inflection curve. In the left area, f<0. Correspondingly, f> 0 in the right area.

If the trajectory always remains in the area of f < 0, the system will always remain stable. Once the trajectory goes through the inflection curve and enters into the area of f > 0, the system will be unstable [17].

Thus, transient stability criterion based on phase-plane trajectory function f can be denoted as:

$$f(\delta,\omega,P_m)<0 \tag{6}$$

In one-machine-infinite-bus (OMIB) system, if P_m and P_e remain invariant, the derivation of (5) with respect to ω is written as:

$$\frac{df}{d\omega}=\frac{\partial f}{\partial\omega}+\frac{\partial f}{\partial\delta}\frac{d\delta}{d\omega}=\frac{1}{M}P_{e\max}\omega^2\sin\delta\frac{1}{D_1}<0 \tag{7}$$

It can be observed from (7) that if P_m and P_{emax} remain invariant, f will increase monotonically along with phase-plane trajectory point(δ, ω) when ω decreases monotonically. Hence, transient stability criterion can be denoted as:

$$f(\delta,\omega_{\min})<0 \tag{8}$$

If the system is stable, the trajectory will swing back once it reaches the farthest point(FEP). Suppose the coordinates of FEP is (δ_r, 0). Then $\omega_{\min}$ is 0 and maximum of f is obtained at FEP(δ_r, 0), satisfying $f(\delta_r, 0)<0$. Otherwise, $\omega_{\min}>0$ and $f(\delta, \omega_{\min})>0$ when system is unstable. Thus, $f(\delta, \omega_{\min})$ can be regard as the transient stability index and reflect transient stability margins.

2.2 Trajectory sensitivity

According to 2.1, if the system is stable, maximum of f is obtained at farthest point (δ_r, 0), satisfying

$$f(\delta_r,0,P_m)=-(P_m-P_{e\max}\sin\delta_r)^2<0 \tag{9}$$

Sensitivity of phase-plane trajectory is defined as the derivation of function f with respect to P_m, as in (10).

$$\frac{df(\delta_r,0,P_m)}{dP_m}=-2(P_m-P_{e\max}\sin\delta_r)(1-P_{e\max}\cos\delta_r\frac{d\delta_r}{dP_m}) \tag{10}$$

Deceleration power is defined as:

$$P_{dec}=P_m-P_{e\max}\sin\delta_r \tag{11}$$

(12) can be obtained by substituting (11) into (10):

$$\frac{df(\delta_r,0,P_m)}{dP_m}=-2P_{dec}(1-P_{e\max}\cos\delta_r\frac{d\delta_r}{dP_m}) \tag{12}$$

When the farthest point approaches unstable equilibrium point (δ_u, ω_u), limit of P_{dec} can be computed as:

$$\lim_{\delta_r\to\delta_u}P_{dec}=P_m-P_{e\max}\sin\delta_u=0 \tag{13}$$

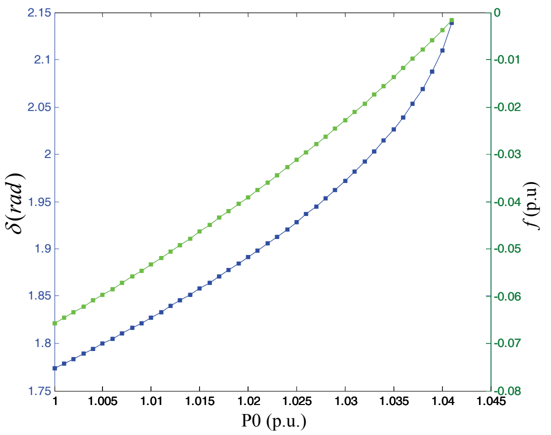

Fig. 2. Comparison of two criteria (δ and f) varying with P_m

According to (13), when the farthest point approaches unstable equilibrium point ($\delta_r\rightarrow\delta_u$), $P_m-P_{emax}\sin\delta_u\rightarrow 0$. Thus, trajectory sensitivity is high-order infinitesimal of rotor angle δ. As a sensitivity index, trajectory sensitivity has favorable linear characteristics, especially when the phase-plane trajectory approaches the unstable equilibrium point. Fig. 2 illustrates the curves of δ and f varying with P_m.

As shown in Fig. 2, the phase-plane trajectory function f has favorable linear characteristics and obvious transient margin. Unlike rotor angle criterion, the threshold of trajectory sensitivity criterion is 0 and not subjected to the outputs of generators. Furthermore, solving function f only needs angle and angular velocity, which guarantees efficiency with the aid of WAMS.

2.3 Phase-plane trajectory method for multi-machine power system

As mentioned above, transient stability can be reflected by variation trend of phase-plane trajectory. In multi-machine power system, after drive a full time-domain simulation to obtain the multi-machine trajectories, all the generators can be separated into two exclusive clusters: one composed of critical machines (CMs), which are responsible for the loss of synchronism, and the other composed of non-CMs (NMs) which correspond to the remaining machines. The correct identification of NMs and CMs is critical for the extended equal-area criterion (EEAC) theory, and systematic approaches for this can be found in [21-23]. Thus, the multi-machine system can be transformed into an equivalent OMIB system, which maintains the same stability characteristics of the original multi-machine system.

Dynamic equation of equivalent bi-machine system can be denoted as

$$\begin{cases}\dfrac{d\delta_{CN}}{dt}=\omega_{CN}\\[2mm]\dfrac{d\omega_{CN}}{dt}=\dfrac{1}{M_{eq}}P_{CN}\end{cases} \tag{14}$$

where, $\begin{cases}M_{eq}=\dfrac{M_C M_N}{M_C+M_N}\\ M_C=\sum\limits_{i\in C}M_i\\ M_N=\sum\limits_{i\in N}M_i\end{cases}$, $\begin{cases}\omega_{CN}=\omega_C-\omega_N\\ \omega_C=\dfrac{1}{M_C}\sum\limits_{i\in C}M_i\omega_i\\ \omega_N=\dfrac{1}{M_N}\sum\limits_{i\in N}M_i\omega_i\end{cases}$,

$\begin{cases}\delta_{CN}=\delta_C-\delta_N\\ \delta_C=\dfrac{1}{M_C}\sum\limits_{i\in C}M_i\delta_i\\ \delta_N=\dfrac{1}{M_N}\sum\limits_{i\in N}M_i\delta_i\end{cases}$,

$$\begin{cases} P_{CN} = \dfrac{M_{eq}}{M_C}(P_{mC} - P_{eC}) - \dfrac{M_{eq}}{M_B}(P_{mC} - P_{eN}) \\ P_{mC} = \sum\limits_{i\in C} P_{mi}, P_{mN} = \sum\limits_{i\in N} P_{mi} \\ P_{eC} = \sum\limits_{i\in C} P_{ei}, P_{eN} = \sum\limits_{i\in N} P_{ei} \end{cases}.$$

where δ_i, ω_i, M_i, P_{mi} and P_{ei} respectively represent the angle, the angular velocity, the inertia time constant, the mechanical input and the electric power of generator i; M_C, M_N are equivalent inertia time constants of CMs and NMs respectively; P_{mC}, P_{mN} are equivalent mechanical inputs of CMs and NMs respectively; P_{eC}, P_{eN} are equivalent electric power of CMs and NMs respectively; δ_C, δ_N are equivalent angles of CMs and NMs respectively; ω_C, ω_N are equivalent angular velocity of CMs and NMs respectively.

Then the transient stability criterion of equivalent OMIB system based on function f_{CN} is:

$$f_{CN}(\delta_{CN}, \omega_{\mathrm{CN\,min}}) < 0 \tag{15}$$

Similarly, $f_{CN}(\delta_{CN}, \omega_{\mathrm{CN\,min}})$ can be regard as the transient stability index and reflect transient stability margins.

In multi-machine system, once the P_{mi} changes, all generators' angles will be disturbed. Moreover, generators with different locations have different impacts on transient stability.

At the given operating point, transient sensitivity matrix is defined as:

$$S_f = [\frac{\partial f_{CN}}{\partial P_1}, \frac{\partial f_{CN}}{\partial P_2}, \ldots, \frac{\partial f_{CN}}{\partial P_i}, \ldots, \frac{\partial f_{CN}}{\partial P_n}] \tag{16}$$

where n is the number of generators, P_i is the mechanical input of generator i; $\frac{\partial f_{CN}}{\partial P_i}$ is the trajectory sensitivity of generator i.

When the P_i changes, transient stability criterion for multi-machine power system is derived as:

$$f_{CN} + S_f \Delta P < 0 \tag{17}$$

where $\Delta \boldsymbol{P}=[\Delta P_1, \Delta P_2, \ldots, \Delta P_n]^{\mathrm{T}}$ is a matrix which expresses the mechanical input change of generators.

The characteristics of the criterion can be summarized as follows:

(1) If $\partial f_{CN}/\partial P_i$ >0 (named as the positive trajectory sensitivity), the increase of P_i will decrease the transient stability of the system; Conversely, the reduction in P_i increases the transient stability of the system.

(2) If $\partial f_{CN}/\partial P_i$ <0 (named as the negative trajectory sensitivity), the increase of P_i will contribute to the transient stability of the system; Conversely, the reduction in P_i decreases the transient stability of the system.

(3) Higher absolute value of $\partial f_{CN}/\partial P_i$ indicates greater effects on transient stability.

3. Coordinated Transient Stability Control for Power System with Wind Farms Integration

Compared with conventional power plants, wind farms are prioritized for its economy and cleanliness. However, intermittency, variability and uncertainty of wind power make the power system operation more complex. Thus, it's necessary to take effective and practical control action to balance the deviation of wind power and maintain the online transient stability.

3.1 Traditional optimal dispatch model

The traditional optimal dispatch model regards the minimum generation adjustment cost of generators as the objective function, shown as follows [24]:

$$\min F(\Delta \boldsymbol{P}) = \sum_{i\in C} \phi_i(\Delta P_i) \tag{18}$$

where $\phi_i(P_i)=a_iP^2_i+b_iP_i+c_i$ denotes the generation cost function in quadratic model.

Then $\phi_i(\Delta P_i)$ can be calculated as follows:

$$\begin{aligned} \phi_i(\Delta P_i) &= \phi_i(P_i + \Delta P_i) - \phi_i(P_i) \\ &= a_i \Delta P^2_i + 2a_i \Delta P_i \cdot P_i + b_i \Delta P_i \end{aligned} \tag{19}$$

where a_i, b_i and c_i are the generation cost coefficients of generator i; C is the combination of dispatchable generators. And $\Delta \boldsymbol{P}=[\Delta P_1, \Delta P_2, \ldots, \Delta P_\mathrm{n}]$ represents the generation adjustment matrix.

Then the traditional optimal dispatch model can be denoted as:

$$\min F(\Delta \boldsymbol{P}) = \sum_{i\in C} \phi_i(\Delta P_i) \tag{20}$$

$$s.t. \quad P_i^{\min} \le P_i + \Delta P_i \le P_i^{\max} \tag{21}$$

$$\sum \Delta P_i = -\Delta P_w \tag{22}$$

where (21) denotes the generation output limits and (22) is power balance equation.

3.2 Coordinated control strategy

When the deviation of wind power is ΔP_w, ΔP_i is the required output adjustment of generator i, satisfying $\sum \Delta P_i = \Delta P_w$. Therefore, the transient stability criterion for power systems with wind farms integration based on phase-plane trajectory can be expressed as:

$$f_{CN} + S_f \Delta P + S_w \Delta P_w < 0 \tag{23}$$

where S_f is the trajectory sensitivity matrix of SGs; $S_w = \partial f_{CN} / \partial P_w$ is the trajectory sensitivity of the wind farm. Because $\sum \Delta P_i = -\Delta P_w$, (23) can be transformed to:

$$f_{CN} + S_c \Delta P < 0 \tag{24}$$

where
$S_c = [\frac{\partial f_{CN}}{\partial P_1} - \frac{\partial f_{CN}}{\partial P_w}, \frac{\partial f_{CN}}{\partial P_2} - \frac{\partial f_{CN}}{\partial P_w}, \ldots, \frac{\partial f_{CN}}{\partial P_i} - \frac{\partial f_{CN}}{\partial P_w}, \ldots, \frac{\partial f_{CN}}{\partial P_n} - \frac{\partial f_{CN}}{\partial P_w}]$.
It denotes the trajectory sensitivity matrix based on the coordinated control strategy.

Suppose $S_{c,i} = \frac{\partial f_{CN}}{\partial P_i} - \frac{\partial f_{CN}}{\partial P_w}$, which represents the coordinated sensitivity of generator i with the deviation of wind farm. According to **2.3**, $S_{c,i}$ is able to reflect the impacts of changing output of generator i on transient stability. And higher absolute value of $S_{c,i}$ indicates greater effects of this corresponding control strategy on transient stability.

From the above, based on the transient stability criterion, the coordinated control model for power systems with wind farms integration can be denoted as:

$$\min F(\Delta \boldsymbol{P}) = \sum_{i \in S_G} \phi_i(\Delta P_i) \tag{25}$$

$$s.t. \quad f_{CN} + S_c \Delta P < 0 \tag{26}$$

$$P_i^{\min} \le P_i + \Delta P_i \le P_i^{\max} \tag{27}$$

$$\sum \Delta P_i = -\Delta P_w \tag{28}$$

The objective function (25) aims to minimize the total generation adjustment cost; (26) expresses the transient stability constraint. (27) denotes the generation output limits and (28) is power balance equation.

Sort $S_{c,i}$ in ascending order to obtain the priority matrix S. Generators with high priority are regard as coordinated generators, whose outputs should be increased to balance the decrease of wind power. Correspondingly, outputs of generators with low priority should be reduced to satisfy transient stability if the operating point is not stable.

3.3 Computation process

The overall computation flowchart of the proposed approach is shown in Fig. 3, and the main steps are detailed as follows:

Step 1: Set the base operating state (note that the operating point when the wind farms have maximum power is set as the base operating point.).

Step 2: Perform time domain simulation under the fault duration t;

Step 3: Identify the CMs and NMs to form the equivalent OMIB system;

Step 4: Calculate the phase-plane trajectory function f_{CN};

Step 5: Assess the transient stability of the system;

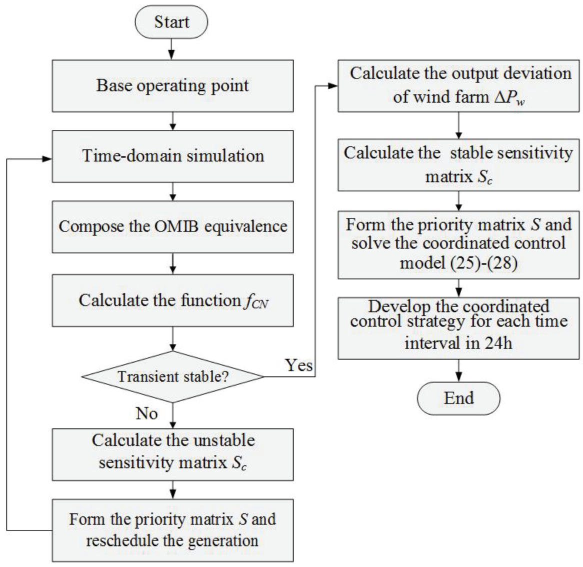

Fig. 3. Computation flowchart of the coordinated control algorithm

If the system is unstable, compute the unstable sensitivity matrix S_c and sort it in ascending order to obtain the priority matrix S. Then reduce the outputs of generators with low priority to satisfy transient stability. After generation rescheduling, go back to **Step 2**;

If the system is stable, move to the next step;

Step 6: Calculate the output deviation of wind farm ΔP_w;

Step 7: Compute the stable sensitivity matrix S_c;

Step 8: Sort $S_{c,i}$ in ascending order to obtain the priority matrix S. Then solving the coordinated control model (25)-(28) to develop coordinated control strategy;

Step 9: Develop the coordinated control strategy for each time interval in 24h then terminate the computation**.**

4. Case Study

The method proposed in the paper is tested on the New England 10-generator 39-bus system, shown in Fig. 4.

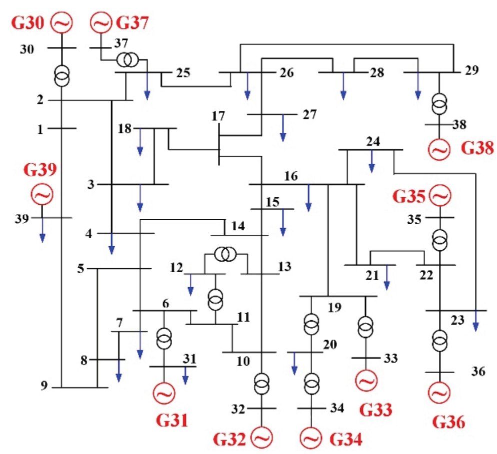

Fig. 4. The New England 10-genrator 39-bus system

Parameters of generators and loads are from [25].

4.1 Case A

In this case, the synchronous motor G30 is replaced by a wind farm with the same capacity. The wind energy turbine model used in this paper is the double fed induction generator, GE1.5MW in BPA4.15. And the maximum power of the wind farm is 225MW. Suppose bus 31 is slack bus. A three phase short-circuit fault occurred in the middle of line 5-8 at 0s and the fault was cleared at 0.12s. The active power outputs of an actual wind farm in a day is shown in Table 1.

The operating point when the wind farms have rated power is set as the base operating point. And the phase-plane trajectory of the system is shown in Fig. 5. Evidently, the system is stable at the base operating point.

With small disturbance on the basic operating point, the coordinated sensitivity of each generator is calculated, summarized in Table 2.

Table 1. The active power outputs of the wind farm in a day

Time (h)	Active outputs (MW)	Time (h)	Active outputs (MW)	Time (h)	Active outputs (MW)
1	21.24	9	92.89	17	35.26
2	15.36	10	48.20	18	50.12
3	19.67	11	29.09	19	65.51
4	18.86	12	66.46	20	80.61
5	33.70	13	94.39	21	108.9
6	18.54	14	36.26	22	158.0
7	21.31	15	9.50	23	180.5
8	12.11	16	30.64	24	185.2

Table 2. Coordinated sensitivity of the SGs

Generator number	Coordinated sensitivity
G31	0.0585
G32	0.0324
G33	0.0249
G34	0.0375
G35	0.0349
G36	0.0372
G37	0.0156
G38	0.0008
G39	-0.0062

Table 3. Maximum adjustable inputs of the SGs

Generator number	ΔP(MW)
G31	slack generator
G32	65
G33	63
G34	50
G35	65
G36	63
G37	54
G38	83
G39	100

Table 4. Generation cost coefficients of the SGs

Generator number	*a*	*b*	*c*
G31	100	330	1000
G32	100	330	1000
G33	110	400	1000
G34	120	550	1000
G35	50	160	1000
G36	100	330	1000
G37	110	440	1000
G38	100	350	1000
G39	110	440	1000

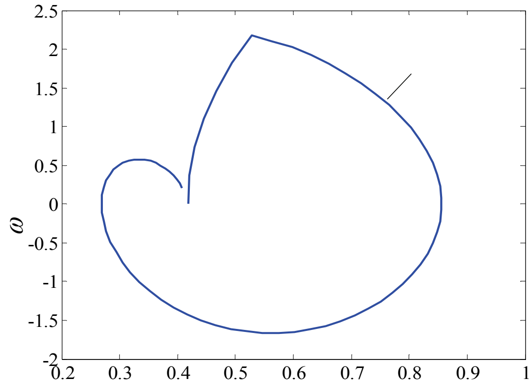

Fig. 5. Equivalent phase-plane trajectory

The maximum adjustable inputs of the SGs and the generation cost coefficients of the SGs are respectively shown in Table 3 and Table 4. The required adjustment of each time interval is calculated based on predictive outputs of the wind farm in Table 1.

Based on the data in Table 3 and Table 4, coordinated control strategy in a day can be developed by solving the proposed coordinated control model (25)-(28):#G35, #G38 and #G39 are orderly selected as coordinated generators to balance the decrease of wind power.

In order to validate the effectiveness and superiority of the proposed method, the system is tested under the 3 following scenarios.

Scenario 1: Apply the traditional optimal dispatch strategy. That is, minimize the generation adjustment cost without considering transient stability constraint.

Scenario 2: Only consider the transient stability constraint and ignore the generation adjustment cost.

Scenario 3: Apply the proposed coordinated control strategy in this paper. That is, consider synthetically the generation adjustment cost and transient stability constraint.

Based on the data in Table 3 and Table 4, #G35 and #G31 should be chosen in sequence to balance the deviation of wind power in Scenario 1; In Scenario 2, #G39, #G38 and #G37 should be selected orderly to balance the deviation of wind power; And in Scenario 3, #G35, #G38 and #G39 should be selected as coordinated generators in sequence to balance the deviation of wind power.

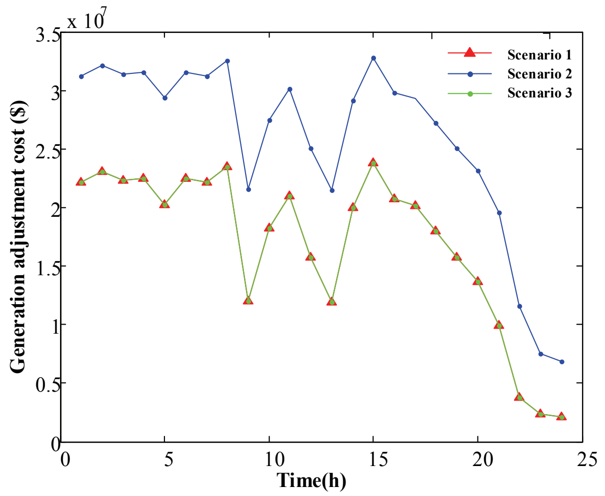

Fig. 6. Comparison of the generation adjustment cost under three scenarios in a day

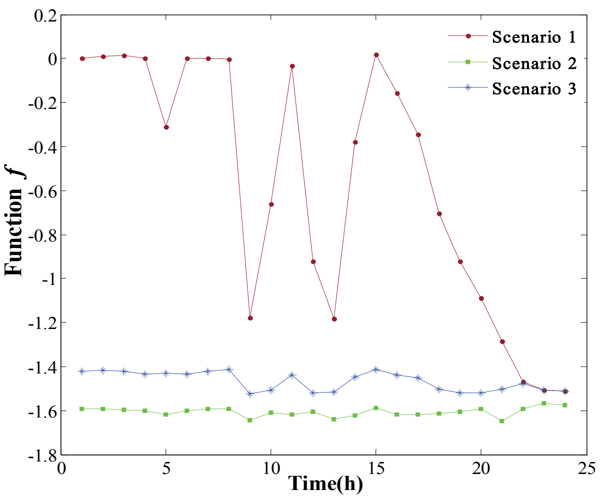

Fig. 7. Comparison of function *f* under three scenarios in a day

The comparison of the generation adjustment cost and the function *f* under three scenarios in a day are shown in Fig. 6 and Fig. 7, respectively.

It can be seen in Fig.6 and Fig.7 that the traditional optimal dispatch strategy in Scenario 1 is able to minimize the generation adjustment cost of SGs. However, the system cannot remain stable when the wind power fluctuates greatly; With the control strategy in Scenario 2, which only considering the transient stability constraint, the system can always maintain transient stability. However, the generation adjustment cost of SGs is markedly increased; In Scenario 3, although the function *f* increases slightly compared with Scenario 2, the system still can maintain transient stability during the whole time. Besides, the generation adjustment cost of SGs is little higher than Scenario 1 but far less than Scenario 2.

The results verify the economy and validity of the proposed coordinated control strategy in this paper.

Table 5. The active output of wind farm 2 in a day

Time (h)	Active outputs (MW)	Time (h)	Active outputs (MW)	Time (h)	Active outputs (MW)
1	45.24	9	33.69	17	42.26
2	23.45	10	28.25	18	35.32
3	33.64	11	56.09	19	65.51
4	15.27	12	23.46	20	68.31
5	43.60	13	44.35	21	78.32
6	12.22	14	21.26	22	80.45
7	31.45	15	12.50	23	86.52
8	12.21	16	14.64	24	90.25

Table 6. Coordinated sensitivity of generators

Generator number	S1	S2
G31	0.0272	0.0026
G32	0.0180	0.0050
G33	0.0087	0.0004
G34	0.0215	0.0066
G35	0.0192	0.0098
G36	0.0229	0.0104
G37	0.0011	-0.0120
G38	-0.0259	-0.0698
G39	-0.0352	-0.0603

Therefore, it can be used to maintain transient stability for power systems with wind farms integration.

4.2 Case B

In order to verify the coordinated control strategy for the system with multiple wind farms integration, wind farm 2 is additionally connected into bus 29 to replace partial output of generator G38 under the same conditions of Case A. The maximum power of wind farm 2 is 99MW and its active power output in a day is shown in Table 5.

Similarly, calculate the coordinated sensitivity S1 and S2, with small disturbance on the basic operating point. And the results are summarized in Table 6.

Similarly, test the system with the different control strategies of the three scenarios in Case A. Based on the data in Table 3 and Table 4, #G35 and #G31 should be chosen in sequence to balance the deviation of wind power in Scenario 1; In Scenario 2, #G39, #G38 and #G37 should be selected orderly to balance the deviation of wind power; In Scenario 3, #G35, #G38 and #G39 should be selected as coordinated generators in sequence to balance the deviation of wind power.

The comparison of the generation adjustment cost and the function *f* under three scenarios in a day are shown in Fig. 8 and Fig. 9, respectively.

As shown in Fig. 8 and Fig. 9, with the proposed coordinated control strategy in Scenario 3, although the function *f* increases slightly compared with Scenario 2, the system can maintain transient stability during the whole time. Besides, the generation adjustment cost of SGs is little higher than Scenario 1 but far less than Scenario 2.

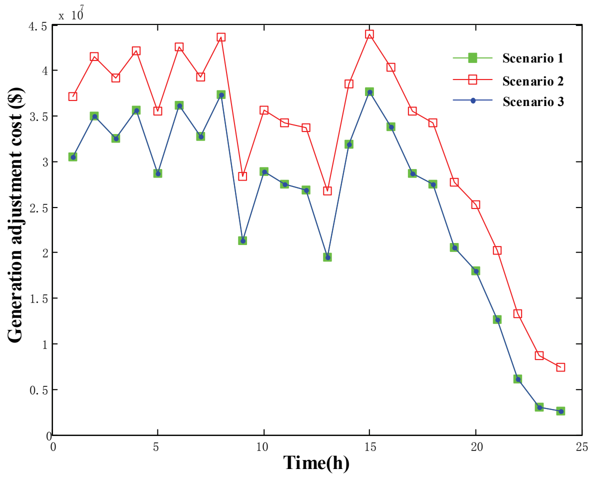

Fig. 8. Comparison of the generation adjustment cost under three scenarios in a day

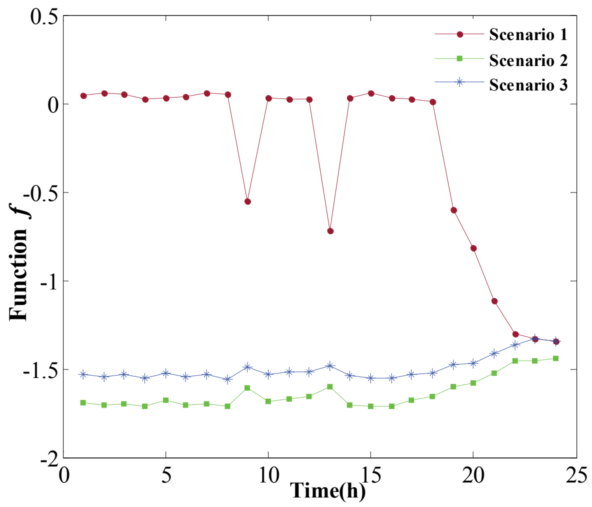

Fig. 9. Comparison of function *f* under three scenarios in a day

Hence, the results in Case A and Case B both verify the economy and validity of the proposed coordinated control strategy in this paper, which can be used to maintain transient stability for power systems with wind farms integration. Besides, the proposed transient stability constraint based on phase-plane trajectory has favorable linear characteristics and obvious transient margin.

5. Conclusion

In order to balance the deviation of wind power and prevent transient instability when outputs of wind farms change, a coordinated control strategy is proposed based on phase-plane trajectory. Based on the coordinated sensitivity of each synchronous generator and the real-time output reduction of wind farm, coordinated generators can be selected to accomplish the coordinated control with wind farms. The tested results in the New England 10-genrator 39-bus system show that the proposed coordinated control strategy can meet the requirements of both economy and security to balance the deviation of wind power and maintain transient stability for power systems with wind farms integration. Besides, the contained transient stability constraint based on phase-plane trajectory has favorable linear characteristics and obvious transient margin compared with rotor angle criterion. Moreover, because the threshold of function *f* is 0, the proposed constraint avoids heuristically selecting thresholds for the maximum relative rotor angle deviation. Therefore, it has great potential for online transient stability control in future application.

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