



Research on Reactive Power and Voltage Coordination Control Strategy for Multi-wind Farm Connecting to Power Grid

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Abstract—In view of the impact of large-scale wind power access on the safe and stable operation of power grid and economic dispatch, a coordinated control strategy for reactive power and voltage optimization of regional power grid with multi-wind farms connected to the grid is proposed. The control strategy considers the optimization of system voltage quality and network loss comprehensively, and uses genetic algorithm to solve the optimization problem. The genetic algorithm based on power flow calculation is improved by utilizing the information of reactive power and voltage sensitivity and reactive power loss sensitivity of regional power grid, which improves the calculation speed of the optimization algorithm and further enhances the real-time performance of reactive power coordination control. Taking a regional power grid in Hami, Xinjiang as an example, the simulation results show that the proposed strategy can effectively improve the voltage quality and network loss of the regional power grid.

Index Terms--Regional power grid; Multi-wind farm; Coordinated control; Voltage quality; Network loss

I. INTRODUCTION

Large-scale wind power access has increasingly prominent impact on the safe and stable operation of power systems and economic dispatch. Guidelines for wind power integration in various countries have made provisions for wind farms to participate in grid operation control, including active power control, frequency control and voltage control^[1-3]. For the regional power grid connected to wind farm, it is one of the important topics to study the reactive power and voltage coordination control of the regional power grid and improve its voltage stability and voltage quality.

In recent years, scholars at home and abroad have carried out extensive research on reactive power and voltage control

of wind farm clusters. References [4] proposes that the reactive power regulating equipment of wind farms and their gathering stations should be taken as a whole for voltage management, and the network loss and voltage deviation of central nodes should be taken as comprehensive objectives for optimal control. References [5] proposes a static voltage stabilization enhancement control strategy for doubly fed wind turbines with fast pitch control. The static voltage control is carried out by setting pitch angle according to wind speed and load arrangement by the central controller of the microgrid. References [6-7] proposed that according to the operation characteristics of reactive power control equipment with different time constants, layered multi-period voltage control for regional power grids with wind farm groups was carried out based on wind power prediction data. Based on the steady-state mathematical model of variable speed constant frequency wind turbines, the method of calculating reactive power limit is proposed in reference [8-10]. The problem of active power and reactive power steady-state operation region of injection system of wind turbines is solved, and the influence of speed control is considered.

The above References only focus on the reactive power and voltage control strategy of a single wind farm, without considering the case of multiple wind farms connected to different grid-connected points. When multiple wind farms are connected to the same regional power grid from different grid-connected points, if each wind farm adopts the constant voltage control mode to control the reactive power and voltage independently only according to its limited information, the voltage quality of the power grid may deteriorate, and even there may be unnecessary reactive power circulation between wind farms. If the constant power factor control mode is adopted, the power grid can not be effectively provided. Reactive power support. Therefore, the optimal and

coordinated control of reactive power sources in the whole region must be considered in the regional power grid connected with multi-wind farms.

In order to effectively solve the above related problems, this paper studies the coordinated voltage control of multiple variable speed constant frequency wind farms connected to the same regional power grid. The control strategy takes into account the optimization of system voltage quality and network loss, and uses genetic algorithm to solve the optimization problem. The genetic algorithm based on power flow calculation is improved by utilizing the information of reactive power and voltage sensitivity and reactive power loss sensitivity of regional power grid, which improves the calculation speed of the optimization algorithm and further enhances the real-time performance of reactive power coordination control.

II. SYSTEM FRAMEWORK OF REACTIVE POWER AND VOLTAGE CONTROL

A. Automatic Voltage Control System

The automatic voltage control system collects real-time operation data of power grid based on the principle of “layered zoning and balancing” of reactive power. On the premise of ensuring the safe and stable operation of power system, on-line optimal closed-loop control of reactive power and voltage equipment is carried out to ensure the qualified voltage quality of power grid, realize the layered zoning balance of reactive power and reduce network losses. In order to avoid reactive power circulation in wind farms, the coordinated control mode of wind turbines should be chosen as reactive power control mode. The wind turbines output reactive power according to the reactive power instructions issued by the wind farm controller. When the communication between the wind farm and the dispatching system is abnormal, the wind farm should switch to the self-control mode. That is to say, the information of wind farm's own data acquisition system is used for constant voltage control or constant power factor control.

B. Reactive Power and Voltage Control System

The realization of coordinated reactive power and voltage control in power grid involves decoupling in three dimensions: target, space and time. Reactive power and voltage control of power grid with multi-wind farms belongs to regional secondary voltage control. Its control objective is mainly to achieve reactive power optimization in regional power grid. Considering the safety, the aim is to improve the voltage stability and quality of the system. Considering economy, the goal is to reduce network loss.

This paper mainly studies the coordinated control of reactive power and voltage in power grid with multi-speed wind farms. In order to highlight the influence of multi-wind farms participating in reactive power and voltage regulation on reactive power optimization, only wind farms are considered as the means of reactive power and voltage regulation. The objective function of reactive power optimization can be expressed as:

$$\min f(Q_w) = \lambda_1 \max |U_i - U_n| + \lambda_2 P_{loss} \quad (1)$$

In equation (1), Q_w is the reactive power output of each wind farm participating in reactive power control. U_i and U_n are voltage magnitude and voltage rating of each node respectively. Ploss is the network loss of the system, which can be calculated by power flow. Both λ_1 and λ_2 are multi-objective weighting coefficients, and they satisfy the sum of λ_1 and λ_2 to be 1.

The first item on the right side of the objective function reflects the security objective of coordinated control. The maximum deviation of node voltage in regional power grid is minimized by control. The second item reflects the economic goal of control, that is, the minimum system loss. By changing the multi-objective weight coefficients, the security and economic objectives of coordinated control are taken into account.

In order to determine the multi-objective weight coefficients, reactive power optimization control is divided into safety control mode and comprehensive control mode according to the maximum voltage deviation of grid node voltage.

$$\begin{cases} \max |U_i - U_n| > U_{sec} \\ \max |U_i - U_n| \leq U_{sec} \end{cases} \quad (2)$$

In equation (2), U_{sec} is the voltage limit of safety control mode, which can be determined according to the target of system voltage quality assessment.

When the maximum node voltage deviation of regional power grid exceeds the safe operation limit U_{sec} , the safety control mode is mainly used to control node voltage recovery. When the maximum node voltage deviation is within the safe operation limit U_{sec} , the integrated control mode is adopted to take into account the security and economic objectives. Once the control mode is determined, the corresponding objective weight coefficient can also be determined. In order to avoid the repeated switching of control modes, the corresponding hysteresis bandwidth should be set in the actual control implementation process.

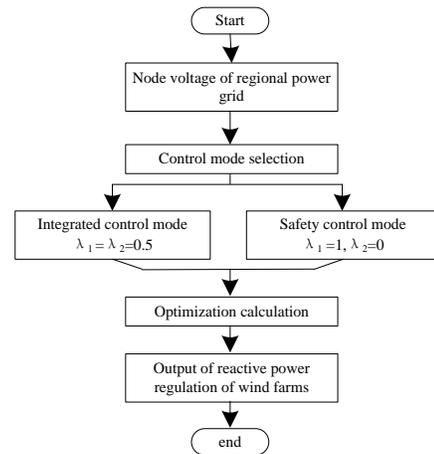


Figure 1. Coordinated control strategy flow

According to the current voltage quality of regional power grid, the coordinated control mode is selected and the target weight coefficient is set. For example, the values of λ_1

and λ_2 are 0.5 in the security control mode., The values of λ_1 value is 1, and the values of λ_2 is 0 in the integrated control mode. Start up the optimization calculation and get the reactive power regulation of each wind farm. The implementation process of coordinated control strategy is shown in Figure 1.

The optimization objective function contains two optimization sub-objectives of different dimensions in formula (1). The sub-targets need to be normalized. In this paper, the normalized objective function is obtained by the following methods:

$$\min f(Q_w) = \lambda_1 \frac{\max |U_i - U_n|}{\max^{(0)} |U_i - U_n|} + \lambda_2 \frac{P_{loss}}{P_{loss}^{(0)}} \quad (3)$$

In formula (3), $\max^{(0)} |U_i - U_n|$ is the maximum voltage deviation before optimization and $P_{loss}^{(0)}$ is the network loss before optimization.

The constraints of the optimization model not only satisfy the system power flow equation, but also satisfy the following inequality constraints.

$$\begin{cases} Q_{w,k}^{\min} \leq Q_{w,k} \leq Q_{w,k}^{\max}, k = 1, 2, \dots, N \\ U_i^{\min} \leq U_i \leq U_i^{\max}, i = 1, 2, \dots, M \end{cases} \quad (4)$$

$Q_{w,k}$ is the reactive power output of the k th wind farm. $Q_{w,k}^{\max}$ and $Q_{w,k}^{\min}$ are upper and lower limits of reactive power output for the k th wind farm respectively. N is the number of wind farms involved in reactive power optimization in the region. U_i^{\max} and U_i^{\min} are the limits of node voltage U_i , respectively. M is the number of voltage nodes participating in the control in the area.

Reactive power output of wind farm is a self-constrained control variable, which can be calculated according to the allowable range of current active power output and power factor of wind farm. The node voltage amplitude as a state variable can be constrained by the following penalty function.

$$P_{en}(U) = \max |U_i - S_{at}(U_i)| \quad (5)$$

$$S_{at}(x) = \begin{cases} x_{\min}, & x < x_{\min} \\ x, & x_{\min} < x < x_{\max} \\ x_{\max}, & x > x_{\max} \end{cases} \quad (6)$$

$S_{at}(x)$ is a saturation function. Therefore, the fitness function f is as follows.

$$f = \lambda_1 \frac{\max |U_i - U_n|}{\max^{(0)} |U_i - U_n|} + \lambda_2 \frac{P_{loss}}{P_{loss}^{(0)}} + \alpha P_{en}(U) \quad (7)$$

The penalty coefficient α increases linearly with the number of iterations in (7).

III. REACTIVE POWER OPTIMIZATION GENETIC ALGORITHM BASED ON SENSITIVITY INFORMATION

In this paper, genetic algorithm is used to solve the above reactive power optimization problem. The genetic algorithm adopts real-coded format. Proportional method is used in selection operation. Uniform crossover is adopted in crossover operation. The uniform mutation method is used for mutation operation. The flow chart of the algorithm is shown in Figure 2.

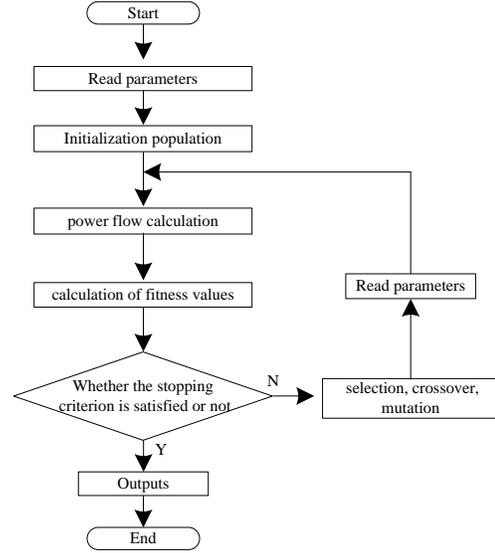


Figure 2. GA based on power flow calculation

The modified equation for power flow calculation can be expressed as shown in (8).

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & N \\ J & L \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta U \end{bmatrix} \quad (8)$$

H , N , J and L are Jacobian block matrices in power flow equations respectively. P , Q , U and δ are active power, reactive power, voltage amplitude and voltage phase angle of the nodes respectively. $\Delta \delta$ and ΔU are the changes of phase angle and amplitude of node voltage respectively.

ΔP and ΔQ are the changes of active and reactive power of injection nodes respectively.

The relationship between voltage amplitude change and reactive power change can be deduced by ignoring the change of active power in the optimization process, such as (9).

$$\Delta U = (-JH^{-1}N + L)^{-1} \Delta Q = S_{Q1} \Delta Q \quad (9)$$

S_{Q1} is the sensitivity matrix of node voltage to reactive power.

Since network loss is a function of both the power of all nodes and the voltage of all nodes, (10) can be obtained.

$$P_{loss} = F(P, Q) = f(\delta, U) \quad (10)$$

Therefore, (10) can be listed.

$$\begin{bmatrix} \left(\frac{\partial P_{loss}}{\partial \mathbf{P}}\right)^T & \left(\frac{\partial P_{loss}}{\partial \mathbf{Q}}\right)^T \end{bmatrix} \begin{bmatrix} \Delta \mathbf{P} \\ \Delta \mathbf{Q} \end{bmatrix} = \begin{bmatrix} \left(\frac{\partial P_{loss}}{\partial \boldsymbol{\delta}}\right)^T & \left(\frac{\partial P_{loss}}{\partial \mathbf{U}}\right)^T \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{\delta} \\ \Delta \mathbf{U} \end{bmatrix} \quad (11)$$

Formula (12) can be obtained by substituting (8) into (11).

$$\begin{bmatrix} \left(\frac{\partial P_{loss}}{\partial \mathbf{P}}\right)^T & \left(\frac{\partial P_{loss}}{\partial \mathbf{Q}}\right)^T \end{bmatrix} \begin{bmatrix} \mathbf{H} & \mathbf{N} \\ \mathbf{J} & \mathbf{L} \end{bmatrix} = \begin{bmatrix} \left(\frac{\partial P_{loss}}{\partial \boldsymbol{\delta}}\right)^T & \left(\frac{\partial P_{loss}}{\partial \mathbf{U}}\right)^T \end{bmatrix} \quad (12)$$

Formula (12) is transposed to form (13).

$$\begin{bmatrix} \mathbf{H} & \mathbf{N} \\ \mathbf{J} & \mathbf{L} \end{bmatrix}^T \begin{bmatrix} \frac{\partial P_{loss}}{\partial \mathbf{P}} \\ \frac{\partial P_{loss}}{\partial \mathbf{Q}} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_{loss}}{\partial \boldsymbol{\delta}} \\ \frac{\partial P_{loss}}{\partial \mathbf{U}} \end{bmatrix} \quad (13)$$

In summary, the sensitivities of available reactive power loss are shown in (14).

$$\mathbf{S}_{Q2} = \frac{\partial P_{loss}}{\partial \mathbf{Q}} = \left((\mathbf{H}^T)^{-1} \mathbf{J}^T - (\mathbf{N}^T)^{-1} \mathbf{L}^T \right) \left((\mathbf{H}^T)^{-1} \mathbf{A} - (\mathbf{N}^T)^{-1} \mathbf{B} \right) \quad (14)$$

In (14), \mathbf{A} equals $\frac{\partial \Delta \mathbf{P}}{\partial \boldsymbol{\delta}}$ and \mathbf{B} equals $\frac{\partial \Delta \mathbf{P}}{\partial \mathbf{U}}$.

Therefore, (15) can be obtained.

$$\Delta P_{loss} = \mathbf{S}_{Q2} \Delta \mathbf{Q} \quad (15)$$

If the current system node voltage is $U_i^{(0)}$, the voltage and reactive power sensitivity is $\mathbf{S}_{Q1}^{(0)}$, and the loss and reactive power sensitivity is $\mathbf{S}_{Q2}^{(0)}$, the objective function of reactive power optimization can be written as (16).

$$\min f(\Delta \mathbf{Q}_W) = \lambda_1 \frac{\max |U_i^{(0)} + \mathbf{S}_{Q1}^{(0)} \Delta \mathbf{Q}_W - U_n|}{\max^{(0)} |U_i - U_n|} + \lambda_2 \frac{P_{loss}^{(0)} + \mathbf{S}_{Q2}^{(0)} \Delta \mathbf{Q}_W}{P_{loss}^{(0)}} + \alpha P_{en}(U) \quad (16)$$

$\Delta \mathbf{Q}_W$ is the regulation increment of reactive power output of wind farm in (16).

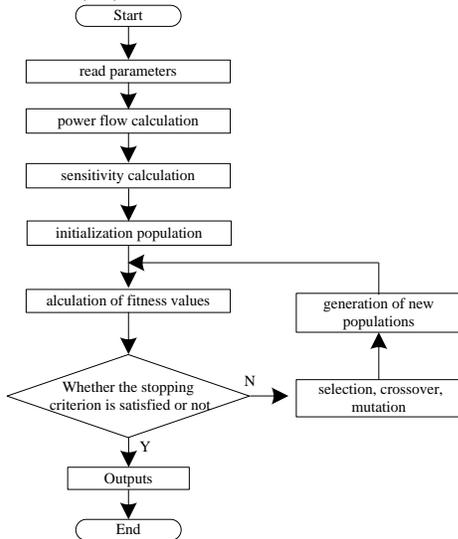


Figure 3. GA based on sensitivities information

The flow chart of genetic algorithm based on sensitivity information is shown in Figure 3. Attention should be paid to the genetic algorithm based on power flow calculation, whose optimization result is reactive power output of wind farm. Based on the sensitivity information of genetic algorithm, the

optimal result is reactive power regulation increment of wind farm. If the reactive power control of wind farm layer only accepts the reactive power output command, the regulation increment should be converted into the reactive power output of wind farm.

IV. EXAMPLE ANALYSIS

In this paper, three VSCF wind farms in Hami region of Xinjiang are simulated and tested by connecting different grid-connected points to the same regional power grid. The test system is shown in Figure 4.

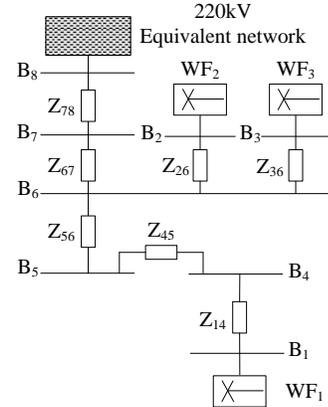


Figure 4. Test power system

The unstated values in the examples are all standard unitary values. The system power base value is 100MW. The voltage base value is 110 kV. The installed capacity of WF1, WF2 and WF3 are 99 MW, 49.5 MW and 20 MW respectively. In the simulation analysis, the whole wind farm is equivalent to a single typhoon generator, and it is considered that the power factor of the wind farm runs from 0.95 (ahead) to 0.95 (lag), the qualified range of node voltage of regional power grid is 0.95 to 1.05, the safe range of operation is 0.9 to 1.1, and the operating range of wind farm is 0.9 to 1.1. The circuit parameters of the test system are shown in Table 1.

Table 1 Parameters of test system

Parameters	Z_{14}	Z_{26}	Z_{36}	Z_{45}	Z_{56}	Z_{67}	Z_{78}
R	0.0119	0.0121	0.0132	0.0255	0.0040	0.0112	0
X	0.0512	0.0375	0.0352	0.0841	0.0141	0.0408	0.0524

The initial calculation conditions are that buses B4, B5 and B7 are connected to local loads of $0.2+j0.16$, $0.5+j0.2$ and $0.8+j0.25$ respectively, and the wind farm is not involved in reactive power regulation of power grid, and is in the operation state of unit power factor. The output active power WF1 is 90MW, WF2 is 40MW, WF3 is 15MW. Before and after optimal regulation, the load remains unchanged and the active output of wind farm remains unchanged. Bus voltage distribution is shown in Table 2 before and under safety mode and comprehensive mode.

In order to evaluate the optimal calculation results of reactive power and voltage, an index is defined as (17).

$$\begin{cases} \Delta U_{\max} = \max |U_i - 1| \\ E = \sum_i |U_i - 1|^2 \end{cases} \quad (17)$$

ΔU_{\max} is the maximum node voltage deviation and E is the voltage characteristic coefficient in (17).

Table 2 Bus voltage distribution of regional power grid under different control strategies

Bus	Control strategy		
	Unit power factor	Safety optimization	Comprehensive optimization
B ₁	0.9496	1.0181	1.0163
B ₂	0.9492	0.9956	0.9955
B ₃	0.9523	0.9895	0.9893
B ₄	0.9393	0.9988	0.9977
B ₅	0.9409	0.9831	0.9831
B ₆	0.9475	0.9867	0.9862
B ₇	0.9596	0.9816	0.9826
B ₈	1	1	1

Before optimal regulation and under optimal regulation in safety mode and integrated mode, voltage quality and loss distribution are shown in Table 3

Table 3 Voltage Quality and Loss Distribution of Regional Power Grid under Different Control Strategies

Index	Control strategy		
	Unit power factor	Safety optimization	Comprehensive optimization
ΔU_{\max}	0.0607	0.0184	0.0174
E	0.0189	0.0013	0.0012
P_{loss}	3.8148	3.0853	3.0915

It is not difficult to see from Table 2 and Table 3 that under the optimized regulation mode, the voltage quality and network loss of the regional power grid are significantly improved compared with the unit power factor control.

V. CONCLUSION

Reactive power and voltage coordinated control of multi-wind farms connected to regional power grid is one of the effective ways to improve the local voltage level and optimize the operation of the system. Make full use of the reactive power regulation capability of variable speed constant frequency wind farm. On the one hand, under the premise of meeting the requirements of wind power Grid-connected guidelines, the investment of reactive power compensation equipment in wind farms can be saved. On the other hand, it can significantly improve voltage quality and reduce local network losses.

This paper presents a coordinated control strategy for reactive power and voltage optimization of regional power grid with multi-wind farms connected to grid. The control strategy takes into account the optimization of system voltage quality and network loss, and improves the genetic algorithm based on power flow calculation by utilizing the information of reactive voltage sensitivity and reactive power loss

sensitivity of regional power grid, which improves the calculation speed of the optimization algorithm and improves the real-time performance of coordinated control.

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