Research on Reactive Power Compensation Strategy Based on Time Series Method in Wind Farms

LIU Guan-qi[1], HU Ting[1], SHAO Long[1], JIAO Shu-ping[2]
[1]North China Electrical Power University, Baoding, 071000, China
[2]Hebei Handan Electric Power Company, Handan, 056000, China

***Abstract*—This paper presents a strategy to make reactive compensation scheme in wind farms, combing wind power prediction with voltage and reactive power integrated control. Firstly, the wind power can be predicted by using ARIMA model. Secondly, the latter two can be calculated since there is a relationship among active power, reactive power and voltage. Therefore, the reactive compensation scheme can be made according to the voltage variation tendency. Being verified with simulation, the scheme can not only solve the problem of capacitor banks being frequently switched, but also make up for the lacks of capacitors by using SVG to ensure the stability of the bus voltage.**

Keywords-time series; reactive power compensation; capacitor banks; SVG

I. INTRODUCTION

As one of the effective means to solve the problem of energy crisis and environmental pollution, wind power generation has been developed rapidly [1]. With the installed capacity of wind farms increasing continuously, so far most of the countries require the ability of adjusting reactive power of wind farms. In order to meet the requirements most wind farms install capacity banks for compensation for reactive power. When the active power output of wind farms vary greatly, the capacity banks may be frequently switched, that will reduce the lifespan of the capacities. Furthermore, over voltage and over current generated while switching capacitor will do harm to the power system and impact security of other electric equipments. In order to solve the problems above, this paper presents a new strategy to make the reactive power compensation plan by taking active power prediction of wind farms into consideration.

II. REACTIVE POWER COMPENSATION STRATEGY BASED ON ACTIVE POWER PREDICTION

The strategy based on constitutes three modules: ARIMA model prediction module, sensitivity calculation module and decision-making module [2]. Fig. 1 shows the structure of the strategy.

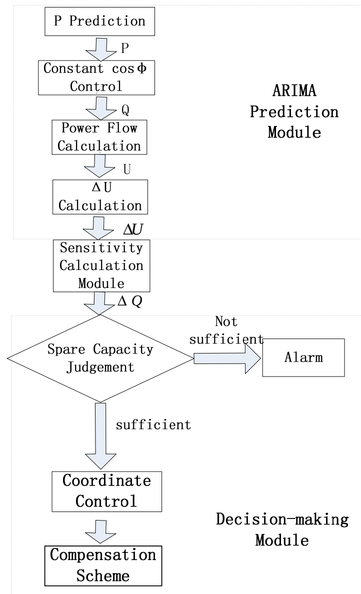

Figure 1. structure of the decision-making system

DFIG (doubly fed induction generators) can generate both active power and reactive power, depending on whether it is constant voltage control or constant power factor control [3]. Due to the present general wind farms operating with constant power factor control, this paper carries on the analysis on the premises that DFIG run in constant power factor mode.

A. ARIMA Model Prediction module.

Based on wind power prediction using ARIMA time series model and the relationship among active power, reactive power and voltage, this module is divided into two function modules: active power prediction module and reactive power/voltage calculation module.

1) ARIMA prediction module

Time series analysis is a kind of simple and effective parameterization analysis method to deal with random data sequence. The active power is such a data sequence and applying time series model to wind power prediction can achieve good result [4].

Having the characteristics of both AR(p) model and MA(q),model ARIMA (p,d,q) is used for the wind power forecasting in this paper[5]. ARMA(p,q) can only describe stationary time series, so most of the time raw data sequence need d order difference disposal. Therefore, the mixed mathematical model ARIMA(p,d,q) is formed, having obvious advantages in prediction issue.

2) reactive power/voltage calculation module

Fluctuations in the output power of the wind turbines is the main reason for voltage fluctuations, in order to simulate the problem, the usual approach is to build a static-mathematical model of wind turbines, taking advantage of the power system analysis software to calculate the voltage values of nodes.

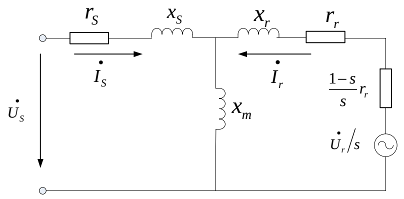

Figure 2. The equivalent circuit of DFIG

The equivalent circuit of the DFIG is shown in Fig. 2, where r_r and r_s respectively represents rotor resistance and stator resistance, while x_r and x_s represents the reactance, s is the slip, x_m represents the magnetizing reactance. Known from DFIG principle, its active power P_e consists of stator active power P_S and rotor active power P_r. Ignore the stator resistance, make $x_{SS} = x_S + x_m$, $U_S = |\dot{U}_S|$, thus P_e can be obtained through formula (1)[6].

$$P_e = P_s + P_r = \frac{r_r x_{ss}^2 \ (P_s^2 + Q_s^2)}{x_m^2 U_s^2} + \frac{2 r_r x_{ss}}{x_m^2} Q_s + (1-s) P_s + \frac{r_r U_S^2}{x_m^2} \quad (1)$$

When taking constant power factor control mode, the output reactive power of stator side is constant, i.e. $Q_S = P_S \tan\varphi$. Due to the reactive power generated by converter is limited, reactive power generated by DFIG can approximately be obtained the through formula (2).

$$Q_e = \frac{-bU_s^2 + Us\sqrt{cU_s^2 + 4P_e a}}{2a} \tan\varphi \quad (2)$$

Where $a = \frac{r_r x_{SS}^2}{x_m^2}(1 + \tan^2 \varphi)$, $b = 1 - s + \frac{2 r_r x_{SS} \tan\varphi}{x_m^2}$, and $c = (1-s)^2 - \frac{4 r_r^2 x_{SS}^2}{x_m^4} + \frac{4 r_r x_{SS} \tan\varphi}{x_m^2}(1-s)$.

Wind farm model commonly uses a wind power unit to represent n, ignored internal line loss and step-up transformer loss, assumed that all units have the same terminal voltage, and is equal to the unknown wind farm bus voltage U_S.

The paper [7] introduces a more elaborate power flow calculation model of DFIG, and it is described as follows:

a) Set the initial value of wind farm voltage as U_S

b) According to the historical data of the output power of the wind farm, predict the DFIG active power P_{ei} by the ARIMA model.

c) According to the characteristics of rotate speed of the wind turbine, calculate the slip s.

d) Calculate the DFIG Q_{ei} through formula (2).

e) P_{ei} and Q_{ei} multiply respectively by the number of units n, obtain the whole active and reactive output of wind farm, and calculate bus voltage U_S' valuing the wind farm as a PQ node into power flow calculation.

f) Compare U_S' with U_S, *if* $|U_S' - U_S| > \varepsilon$, $\varepsilon = 1 \times 10^{-5}$, then order $U_S = \frac{1}{2}(U_S + U_S')$, back to step d) to calculate Q_{ei} and then the subsequent steps until the voltage difference can satisfy $|U_S' - U_s| < \varepsilon$.

B. *Sensitivity Calculation Module*

Generally speaking, sensitivity is a state vector which characterizes the sensitive degree of operating state by changing control vectors and disturbance vectors. The sensitivity equation of power flow calculation could be expressed as formula (3):

$$\begin{bmatrix} J_H & J_N \\ J_J & J_L \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta U \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (3)$$

In the formula, J_H, J_N, J_J, J_L are Jacobi partitioned matrix of power flow equation, the elements of Jacobi matrix are respectively $J_H = \partial P / \partial\theta$, $J_N = (\partial P / \partial U) * U$, $J_J = \partial Q / \partial\theta$, $J_L = (\partial Q / \partial U) * U$. ΔP, ΔQ, ΔU, $\Delta\theta$ are the deviation of corresponding active power, reactive power, voltage amplitude and voltage phase angle, respectively.

When $\Delta P = 0$, it can be concluded that $\Delta Q = (J_L - J_J J_H^{-1} J_N)\Delta U$. In consideration of reactance is bigger than resistance in electric transmission line it can be concluded further as formula (5):

$$\Delta Q = J_L \Delta U \quad (5)$$

Finally, from formula (5) we can conclude ΔQ which determined by the migration of voltage ΔU.

C. *Decision-making Module*

Based on the results of sensitivity calculation module, the decision-making module would judge whether the spare capacity of capacitor banks and SVG installed in wind farm could satisfy the demand for adjustment of reactive power. If the spare capacity is not sufficient, control system will send out alarm to dispatcher so that they can make corresponding solutions in advance. If the spare capacity could satisfy the demand, system will work out a reactive power regulation scheme for next ten hours, including the numbers of capacitor banks, the operating state of SVG and their switching time.

In the wind farm, its voltage and reactive power control equipments include discrete compensation device (Capacitor banks) and continuous adjustment device (SVG). Switching of capacitor banks can only achieve stepped adjustment for voltage and reactive power, its range of adjustment is major and it can't realize surpassingly accurate adjustment while

SVG could achieve continuous adjustment. Based on the principle that "discrete device take priority action and continuous device make accurate adjustment" [8], reactive power coordinate strategy between capacitor banks and SVG is proposed in the article, according to the coordinate strategy, reactive power vacancy will be assigned between capacitor banks and SVG.

When the output of SVG is Q_S, the capacity of one group of capacitor banks is Q_C, ΔQ is the reactive power demand from the sensitivity calculation module, the coordinate strategy could be described as follow:

a) If $\Delta Q > 0$, reactive power should be increased.

When $Q_S + \Delta Q \geq \Delta Q_C$, input one group of capacitor banks, meanwhile change the output of SVG to $Q_S + \Delta Q - Q_C$.

When $Q_S + \Delta Q < \Delta Q_C$, change the output of SVG to $Q_S + \Delta Q$;

b) If $\Delta Q < 0$, reactive power should be decreased.

When $Q_S + \Delta Q \leq -Q_C$, cut off one group of capacitor banks, meanwhile change the output of SVG to $Q_S + \Delta Q + Q_C$.

When $Q_S + \Delta Q > -Q_C$, change the output of SVG to $Q_S + \Delta Q$;

III. SIMULATION ANALYSIS

Taking a wind farm in Inner Mongolia as an example, the simulation model of the in-grid wind farm is built at MATLAB/SIMULINK environment. The model simulates a wind farm with 40MW installed capacity, which is integrated into the grid through a step-up transformer and then is connected to a 110kV bus of 220kV substation by a 110kV transmission line(LGJ-240) of 22km length. There are four groups of capacitors, each with 2000kVar capacitance, and a 5Mvar-capacitance SVG installed at the low voltage side of the step-up transformer.

1) Time series is made up by 4320 active power data picked every 10 minutes from wind active power sequence from 29 May 2011 to 27 June 2011. Then the data of the former 29 days is used to forecast its next 10 hours data by using ARIMA model at MATLAB environment. The outcome of the prediction is shown in Fig. 3.

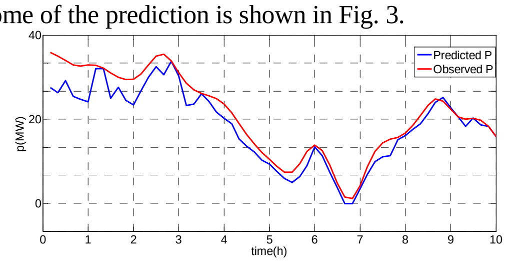

Figure 3. Prediction results of active power

2) Due to the present general wind farms operating with constant factor control, the wind turbines are set to work in constant power factor mode, i.e. $\cos\varphi = 0.98$. According to the power flow calculation model of DFIG, the reactive power absorbed by wind turbines and the bus voltage can be figured out by using the prediction result of the active power. In Fig. 4 is the calculation results of the reactive power, while the calculation results of the bus voltage is shown in Fig. 5.

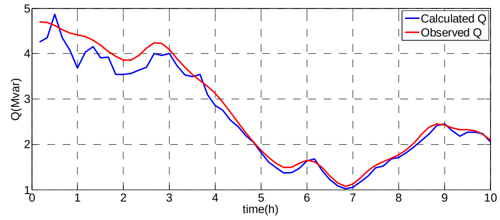

Figure 4. Calculation result of the reactive power

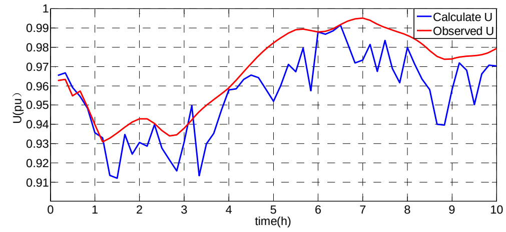

Figure 5. Calculation result of the bus voltage

3) With ΔQ figured out in sensitivity calculation module, reactive compensation scheme can be made according to coordination strategy, which is "discrete device take priority action and continuous device make accurate adjustment". Then the lack of reactive power ΔQ is being divided between capacitor banks and SVG. The reactive compensation scheme being made is shown in Fig. 6 and Fig. 7. Then the reactive compensation scheme is verified by simulation and the bus voltage after adjustment is shown in Fig. 8.

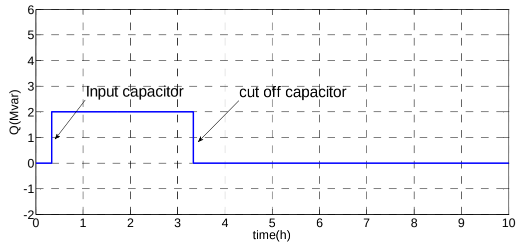

Figure 6. Capacitor compensation scheme

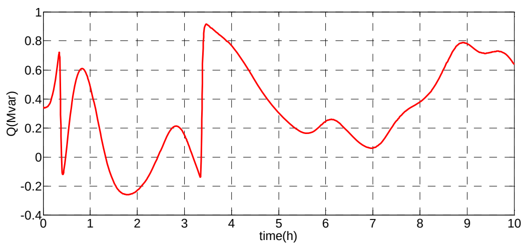

Figure 7. SVG compensation scheme

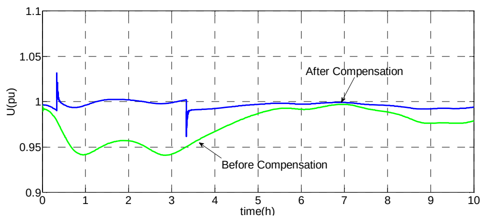

Figure 8. Bus voltage of wind farm before/after compensation

IV. CONCLUSION AND OUTLOOK

This article has presented a theory to make reactive power compensation scheme in wind farms, taking wind power prediction which is based on ARIMA model into consideration. After the active power being predicted, the reactive power and bus voltage, as well as the reactive power shortage, can be calculated out so that an effective reactive scheme is to be made to ensure the stability of the output voltage. In this way, SVG's fast adjustment ability can mitigate the impact caused by capacitor switching on the system voltage. At the same time, the switching times of capacitor can be decreased so that capacitor fault rate and maintenance work are reduced.

Meant to be prediction and guidance, the strategy should be integrated with real-time reactive power compensation in order to ensure the bus voltage and the system stability perfectly. Since the specific conditions of each wind farm is different, it is essential to take the wind farm's real operation condition into consideration so that the reactive power compensation scheme can be made according to the strategy.

Software for the system is expected to be developed to implement the strategy. Therefore, for other wind farms, the reactive compensation software can be used by transmitting simulation model.

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