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Coordinating Control of Reactive Power Optimization in Distribution Power System with Distributed Wind Energy

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Abstract

Distributed generation (DG) systems are considered an integral part in future distribution power system. The reactive power injections from DG units, are seen as a cost-effective solution for distribution system voltage support, energy saving, and reliability improvement. This paper proposes a coordinating control method of reactive power optimization in distribution power system with distributed wind energy. The reactive capability limits of doubly fed induction generator (DFIG) are included in the optimization model. The problem of reactive power output/absorb of adjustable compensating capacitor and wind turbine (WT) is formulated as constrained conditions; differential evolution algorithm (DE) integrating depth-first search is developed to effectively obtain optimal solutions. The proposed algorithm is applied to a practical test system and results are compared and presented.

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Keywords: Wind energy, reactive power optimization, distribution power system

1. Introduction

Distributed generation is the direction of future power industry. Wind energy is the most widely used clean renewable energy. Distributed wind turbines(WT) are connected to the grid as distributed power sources and have brought significant impact on the system power flow distribution, voltage level and transmission loss.

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Adequate voltage stability margin needs to be obtained through the appropriate scheduling of the reactive power resources [1].

Asynchronous wind turbines have simple structure and easy interconnection, but need to absorb reactive power from system in running state, there is no excitation device and capability of voltage regulation[2]. Currently, the most common technology used is the doubly fed induction generator (DFIG), which is able to provide reactive power support. A large variety of control strategies can be used in the operation of DFIG

The author in [3] has proposed a wind turbine control strategy in which the converters of grid side and rotor side are reserves of each other. In [4], a method to calculate the reactive power limit of system with DFIG considering grid-side converter reactive power limit is proposed, and the DFIG wind farm are used for reactive power compensation. [5] focused on including the reactive power capability of the DFIG turbines directly in the optimization formulation, and proposed a multiobjective reactive power planning strategy for WF and transmission system devices.

In this paper, we focus on the reactive power optimization of distributed system with distributed wind power, asynchronous wind turbines, adjustable compensating capacitor and DFIG technology is considered, and the reactive power capability of converter also taking into consideration.

Nomenclature

$\dot{U}_s$	the rotor side voltage	$\cos\varphi$	the power factor
$\dot{I}_s$	the stator side current	$\dot{I}_r$	the rotor current
R_s	the stator resistance	R_r	the rotor side resistance
x_s	the rotor side leakage reactance	x_r	the rotor side leakage reactance
x_m	the excitation reactance	s	the slip ratio
P_s Q_s	the active power and reactive power generated or absorbed by stator side		
P_r Q_r	the active power and reactive power generated or absorbed by rotor side		
Q_g	the reactive power of DFIG emits to system	Q_{Asy}	the reactive power output of asynchronous WT
P_c Q_c	the active power and reactive power of GSC input from system		
P	the active power output of asynchronous WT	V	the output voltage of asynchronous WT
x_1	the stator leakage reactance	x_2	the rotor leakage reactance

2. Mathematic model of wind turbine generator

2.1 Mathematic model of Variable Speed Constant Frequency Wind Turbine Generator

The DFIG has two set of windings including rotor winding and stator winding. The stator winding is connected directly to the grid through grid-side converter, GSC. The DC side voltage is controlled by GSC, and the power factor is adjusted according to the demand of grid.

The value is set to positive when rotor and stator generating active power and inductive reactive power into grid. Then the power injected to the system by DFIG can be written as:

$$P_e = P_s + P_r \tag{1}$$

$$Q_e = Q_s + Q_r \tag{2}$$

There are two main operating mode for DFIG: Constant power factor and constant voltage. Where Q_r can be neglected, then we have $Q_e = Q_s$. When the stator side voltage of wind turbine is constant, its reactive power adjustment range is influenced by the thermal limit current of stator winding and rotor winding, and the maximum current of converter. The maximum current of converter is the main impact factor. The rotor current range is determined by the converter current range. Let the maximum converter current be $I_{r\max}$, which is usually 150% of the rated current[6], then we have:

$$P_s^2 + (Q_s + \frac{|\dot{U}_s|^2}{X_{ss}})^2 \le \frac{|\dot{U}_s|^2 x_m^2 I_{r\max}^2}{X_{ss}^2} \tag{3}$$

The stator side reactive power range can be obtained from (3):

$$\begin{aligned} Q_{s\min} &= -\frac{3|U_s|^2}{2X_s} - \sqrt{(\frac{2}{3}\frac{X_m}{X_s}|U_s| I_{r\max})^2 - P_s^2} \\ Q_{s\max} &= -\frac{3|U_s|^2}{2X_s} + \sqrt{(\frac{2}{3}\frac{X_m}{X_s}|U_s| I_{r\max})^2 - P_s^2} \end{aligned} \tag{4}$$

2.2 Reactive power limit of GSC

The essence of GSC is a voltage type PWM rectifier, the AC side has the unique characteristics of a controlled current source, it can run in four quadrant. The GSC usually run in unit power factor condition, if P_c and Q_c are active power and reactive power of GSC input from system, then $Q_c = 0$, capacity selection of GSC only need to consider the maximum slip-active power of DFIG.

According to the wind power system with the maximum slip-active power to design power size of GSC, line loss and breaker loss are taking into consideration. If $P_{c\max}$ is the maximum active power of GSC, the reactive power of it emits or absorbs calculate as equation (5)-(6):

$$P_c^2 + Q_c^2 \le P_{c\max}^2 \tag{5}$$

$$\begin{aligned} Q_{c\min} &= -\sqrt{P_{c\max}^2 - [s/(1-s)]^2 P_{mec}^2} \\ Q_{c\max} &= \sqrt{P_{c\max}^2 - [s/(1-s)]^2 P_{mec}^2} \end{aligned} \tag{6}$$

2.3 Asynchronous wind turbine model

The active-reactive power relationship of asynchronous WT system showed in (7)

$$Q_{Asy} = f(V) = -\frac{V^2}{x_m} + \frac{-V^2 + \sqrt{V^4 - 4P^2x^2}}{2x} \tag{7}$$

Where P is the active power output, V is output voltage, $x = x_1 + x_2$.

3. The reactive power optimization model of power distribution system with distributed wind turbines

3.1 Mathematical model

The objective of reactive power optimization model is to reduce the loss of system, reactive power optimization is defined as the minimization of reactive power losses by controlling a number of control variables:

$$\min \sum_{i-1}^{24} Q_{loss} \tag{8}$$

$$s.t.\begin{cases} h(u,x)=0, k=1,2,...,n \\ g(u,x)\le 0, k=1,2,...,n \end{cases} \tag{9}$$

Where h is equality constraint, namely power flow equation, g is inequality constraints, including the branch power restriction, the node voltage constraints and upper and lower limits of control variables; u and x represent control variables and state variables respectively.

3.2 Power flow model of distribution power system based on depth search

The benefit of the power flow calculation methods based on depth search is that could ignore the specific network in radial topology, only need to know the base information of the node structure and the branch structure. In this paper, choose the voltage deviation as the termination condition of power flow calculation:

$$\max(\left|U_i^j - U_i^{j-1}\right|) \le \varepsilon \tag{10}$$

Where ε is constant, ε =10^{-5}. Then compute injection current of non-end nodes piecewise according to the level attribute, more details in [7]. Nodal attributes including:

$$\inf_i = \{i, p_i, q_i, l, l_{\max}, a\} \tag{11}$$

Where i is node number, p_i is nodal active power, q_i is nodal reactive power, l is hierarchy number, $l_{\max}$ is the maximum hierarchy number, a is node type.

3.3 Solution procedure based on differential evolution algorithm

Classic differential evolution involves two stages: initialization and evolution. Initialization generates an initial population P^0. Then P^0 evolves to P^1, P^1 evolves to P^2, … ,until the termination conditions are fulfilled. While evolving from P^n to P^{n+1}, the three evolutionary operations, namely, differential mutation, crossover and selection are executed in sequence.

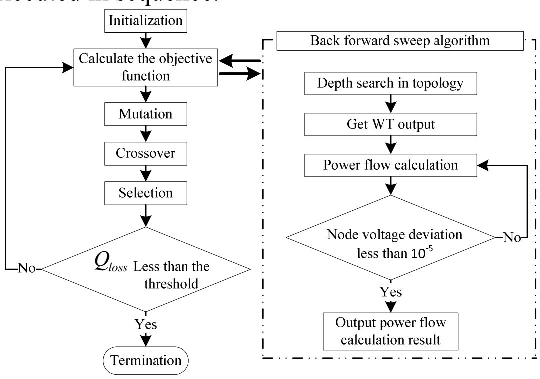

Fig 1 Coordinating control method of reactive power optimization with distributed wind energy

Termination conditions: when Q_{loss} less than the threshold, algorithm terminates. The whole solution procedure is given in Fig.1. The threshold of reactive power loss employ the average reactive power loss of network without WT, and considering the termination condition can not be satisfied, set the maximum number of iterations to avoid endless loop, maximum number is 500.

4. Reactive Power Optimization and Verification With Distribution WT

4.1 Access form of distribution WT

In this paper, chose a distribution power system as test case, bus voltage is 1.05(p.u.), reference power is 100 MVA, reference voltage is 10 KV. The chosen network is radial topology including three lines contain 424 nodes, which the line 1 has 224 nodes, the line 2 has 119 nodes and the line 3 has 81 nodes.

There are 6 access points which all in frontier nodes, shown in Table 1. Because the WT output power fluctuate, given the wind speed random in the case, according to the wind power characteristic curve to ensure the WT output.

Table 1. WT access points

Access points of DFIG	Combined access points	Line
109	139	1
232	239	2
355	359	3

4.2 Coordinating control of reactive power optimization in distribution power system with distributed wind energy

The node of 1 to 244 belongs to line 1, 225-343 belongs to line 2, 344-424 belongs to line 3, Fig.2(a) shows the total network voltage level without distributed wind energy and Fig.2(b) shows the nodal voltage state after reactive power optimization.

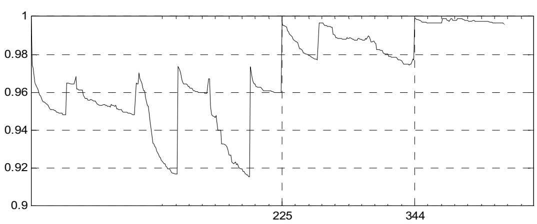

Fig 2(a) Voltage level without distributed wind energy

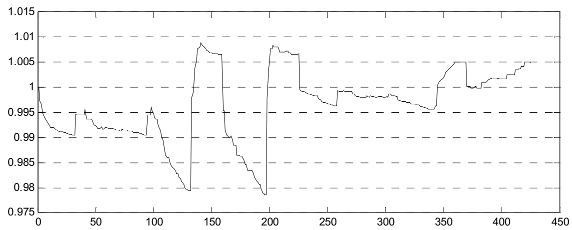

Fig 2(b) Voltage level without distributed wind energy

The figures above show that nodal voltage of line 1 are in low state, line 2 and 3 are higher simultaneously when there is no reactive power compensation and wind energy access. The reactive power optimization efficiency considering the reactive power limit of WT shows in Fig.(3)-(5) , the left is the access point voltage state before optimization, and the right is after optimization.

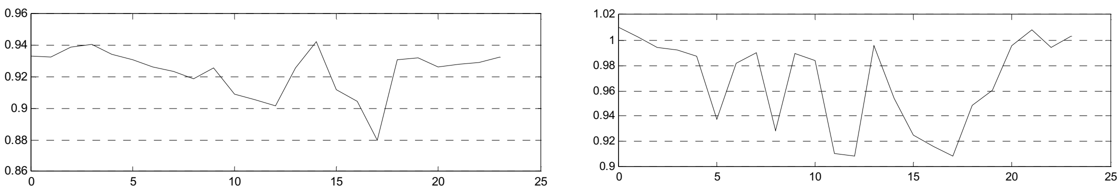

Fig 3 Voltage state of node 109

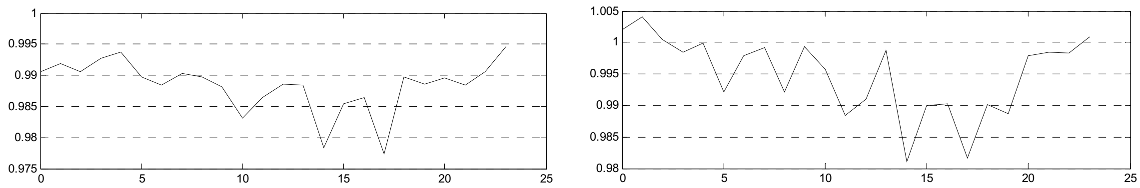

Fig 4 Voltage state of node 232

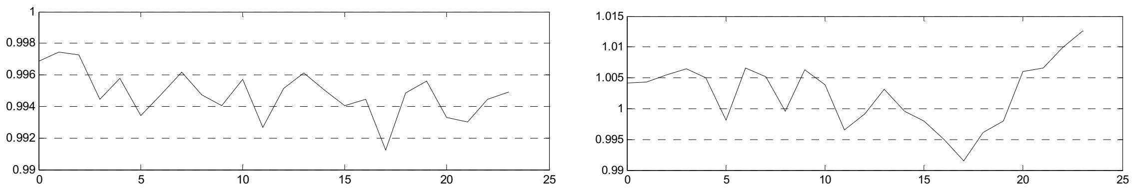

Fig 5 Voltage state of node 355

In line 1, node voltage level increased significantly, all of nodes with low voltage rise within the allowable range. Fig.(3)-(5) show the voltage variation in 24 hours between WT accessed and the day before access. After WT accessed, voltage of total access points improved, where node 109 is the most significant. The switch time optimization result of adjustable compensating capacitor shows in Table 2, and the total reactive power loss decreased from 1.951MWh to 1.678MWh.

Table 2. Switch time optimization result of adjustable compensating capacitor

Adjustable compensating capacitor	Access point	Line	Time of switch on	Time of switch off
1	139	1	5	13
2	239	2	7	15
3	359	3	10	22

5. Conclusion

This paper has presented a optimization method for reactive power optimization of distribution system with incorporating DFIG reactive capability and asynchronous WT. The reactive capabilities of DFIG including the reactive power limit of GSC have been emphasized in this paper.

Acknowledgements

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