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Reactive power control of wind farm made up with doubly fed induction generators in distribution system

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ABSTRACT

In recent years, the number of small size wind farm made up with doubly fed induction generators (DFIG) located within the distribution system is rapidly increasing. DFIG can be utilized as the continuous reactive power source to support system voltage control by taking advantage of their reactive power control capability. In this paper, considering both reactive power control and distribution network reconfiguration can be used to reduce power losses and improve voltage profile, a joint optimization algorithm of combining reactive power control of wind farm and network reconfiguration is proposed to obtain the optimal reactive power output of wind farm and network structure simultaneously. The proposed algorithm has been successfully implemented on the 16 bus distribution network and the results obtained demonstrate the efficiency of the algorithm.

1. Introduction

Wind energy is one of the most important and promising renewable energy resources in the world. The penetration of the wind energy in electrical system is rapidly increasing. Currently, a growing number of small size wind farms used as DG sources are located within the distribution system. Installing wind farm in the distribution system can defer the investments for the distribution system expansion, but the intermittent and volatile nature of wind power generation may impact distribution system voltages, frequency and generation adequacy, so the electrical parameters of the distribution network have to be maintained [1–4]. When wind energy penetration is high, voltage control in the distribution system becomes particularly important. As the consequences, in many countries, the new established grid codes demand that wind farm made up with doubly fed induction generators should actively participate in improving voltage control in the distribution system [5].

The variable-speed wind turbine equipped with DFIG is the most popularly employed generator for the recently built wind farm. The variable-speed wind turbine has the ability to obtain the maximum active power from wind speed and control the reactive power independently [6,7]. Utilizing DFIG reactive power control capability, wind farm composed of DFIG can be used as the continuous reactive power source to support system voltage control with fewer costs on the reactive power compensation device. Wind farm reactive power control can reduce power losses and improve the voltage profile at the user terminal by providing reactive power compensation in distribution systems. Wind farm reactive power output is controlled by the system optimal operation condition and the reactive power control capability of each DFIG wind turbine.

There are many previous works on wind farm reactive power control. Ref. [8] proposes a detailed mathematical model of the DFIG and two alternative simulation models for the analysis of both the active and reactive power performances associated with a wind farm constituted exclusively by DFIG. Ref. [9] proposes an optimized dispatch control strategy for active and reactive powers delivered by a doubly fed induction generator in a wind park. Ref. [10] presents a control strategy developed for the reactive power regulation of wind farms made up with DFIG, in order to contribute to the voltage regulation of the electrical grid to which farms are connected. Ref. [11] describes the relation between active and reactive power in order to keep each DFIG operating inside the maximum stator and rotor currents and the steady state stability limit. Ref. [12] describes a PI-based control algorithm to govern the net reactive power flowing between wind farms composed of doubly fed induction generators and the grid.

Network reconfiguration is one of the most significant control schemes in the distribution system, which alters the topological structure of distribution feeders by changing open/closed status of sectionalizing and tie switches. The purpose of the optimal distribution network reconfiguration problem is to identify an

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optimal radial operating structure that reduces real power losses or improves voltage profile while satisfying operating constraints. Most of the methods used for the network reconfiguration in the literature are heuristic methods [13–15]. The other class of approaches applied to network reconfiguration problem is based on artificial intelligence searching algorithms, such as genetic algorithm, simulated annealing algorithm, tabu search algorithm, etc. [16–18].

However, the previous studies perform wind farm reactive power control with no consideration of network reconfiguration, or perform network reconfiguration with no consideration of wind farm reactive power control, which cannot find the optimal network structure and wind farm reactive power output at the same time for system optimal operation condition.

In this paper, a joint optimization algorithm of combining reactive power control of wind farm and network reconfiguration is proposed to obtain the optimal reactive power output of wind farm and the optimal network structure simultaneity. To find the optimal reactive power output of wind farm, an improved hybrid particle swarm optimization with wavelet mutation (HPSOWM) algorithm is utilized, meanwhile a binary particle swarm optimization (BPSO) algorithm is developed to find the optimal network structure for each particle updating instance at each iteration of wind farm reactive power output optimization algorithm.

2. System model and control

2.1. DFIG wind turbine model

Fig. 1 shows the model of DFIG wind turbine consisting of a pitch controlled wind turbine and an induction generator [19]. The stator of the DFIG is directly connected to the grid, while the rotor is connected to a converter consisting of two back-to-back PWM inverters, which allows direct control of the rotor currents. Direct control of the rotor currents allows for variable-speed operation and reactive power control thus DFIG can operate at a higher efficiency over a wide range of wind speeds and help provide voltage support for the grid. These characteristics make the DFIG ideal for use as a wind generator.

Generally, the reference value of the active power that a DFIG should generate is established through optimum power curves, which provide the active power as a function of the generator rotational speed [19]. Fig. 2 shows a power curve for a typical 1500 kW DFIG wind turbine. Such curves are derived as a result of analysis of the wind turbine aerodynamics, and by defining the maximum mechanical power the DFIG can extract from the wind at any angular speed [8,12].

2.2. DFIG capability limits curve

Fig. 3 shows the single-phase equivalent circuit of the DFIG, where U_S is the stator voltage, U_R is the rotor voltage, I_S is the stator current, I_R is the rotor current, R_S is the stator resistance, R_R is the rotor resistance, X_S is the stator reactance, X_R is the rotor reactance, X_M is the mutual reactance, and s is the slip.

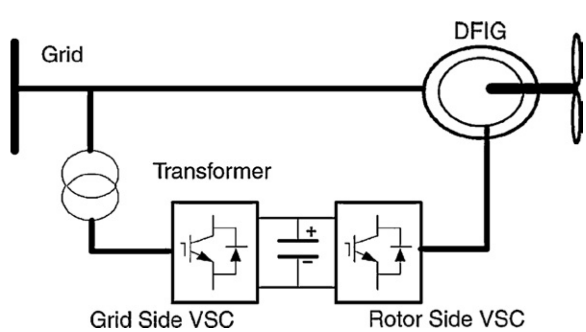

Fig. 1. DFIG wind turbine.

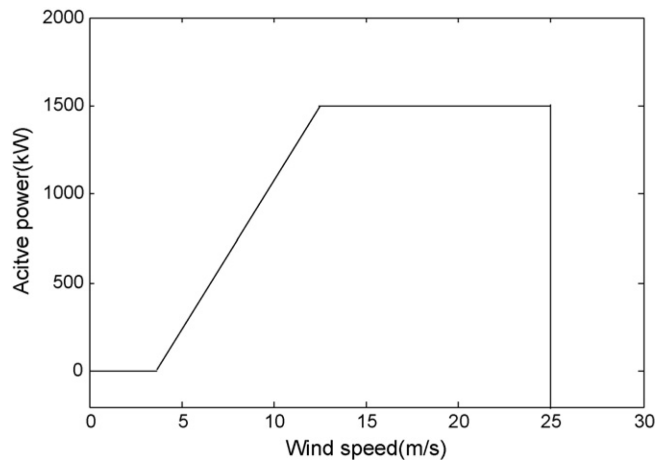

Fig. 2. Power curve for a typical 1500 kW DFIG wind turbine.

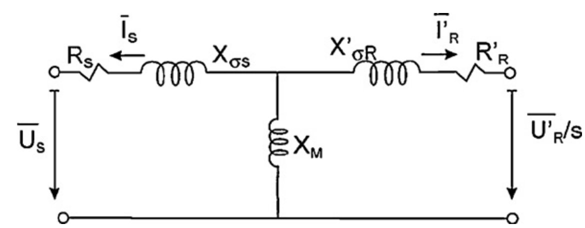

Fig. 3. DFIG equivalent circuit.

The doubly fed asynchronous generator converts the wind turbine mechanical power into electrical power that is fed into the grid through the stator and the rotor by means of a frequency converter consisting of two back-to-back inverters.

The total active power of the DFIG fed into the grid is the sum of stator and rotor active power.

$$P_T = P_S + P_R \tag{1}$$

Taking into account that

$$P_R = -sP_S \tag{2}$$

$$P_T = (1-s)P_S \tag{3}$$

where P_T is the total active power of the DFIG fed into the grid, P_S is the stator active power, and P_R is the rotor active power.

In opposition to active power, total reactive power fed into the grid is not the addition of stator and rotor reactive power because rotor reactive power cannot flow through the frequency converter. The grid side inverter of the frequency converter has its own reactive power capability, so total reactive power fed into the grid is the sum of the stator and the grid side inverter reactive power. Usually, in the commercial systems, this inverter works with unity power factor, being total reactive power, in such case, equal to stator reactive power.

$$Q_T = Q_S \tag{4}$$

The stator active and reactive power can be expressed as a function of stator and rotor maximum allowable current [11]:

$$P_S^2 + Q_S^2 = (3U_S I_S)^2 \tag{5}$$

$$P_S^2 + \left(Q_S + 3\frac{U_S^2}{X_S}\right)^2 = \left(3\frac{X_M}{X_S}U_S I_R\right)^2 \tag{6}$$