Electric Power Systems Research 78 (2008) 1837–1840

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Reactive power capability of doubly fed asynchronous generators

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ARTICLE INFO

Article history:
Received 16 May 2007
Received in revised form 9 January 2008
Accepted 24 February 2008
Available online 27 June 2008

Keywords:
Doubly fed asynchronous generator
Reactive power capability
Synchronous generator

ABSTRACT

While synchronous generator reactive power capability has been extensively treated in the bibliography, reactive capability of doubly fed asynchronous generator (DFAG) has not yet been studied. This kind of generator is widely used in wind energy, and its reactive power capability must be known in order to plan the reactive capability of wind farms as required by grid codes. Active and reactive power output of DFAGs can be expressed as a function of the terminal voltage and the internal voltage, allowing the graphical representation of the power capability limits in a similar way as the synchronous generator.

1. Introduction

Large-scale wind energy integration is becoming a fact as social concerns on clean and sustainable energy increase.

In many countries like Germany, Spain, Denmark, etc., new grid codes have been established [1] demanding new wind farms to behave as conventional power plants.

Main requirements established in these new grid codes are the so-called wind turbine low voltage ride through capability and reactive power capability. The first specification aims to improve transient stability in a power system with a high penetration of wind energy, while the second specification aims to support voltage control in such power system.

Main ancillary services in a power system are power-frequency control and voltage control. These services must be provided by each generator connected to the grid. In order to provide the ancillary service of voltage control, generators must have some reactive power capability as required by the corresponding grid code.

In Spain, the voltage control ancillary service [2] specifies that each generator must provide certain margin of reactive power capability (established as ±15% of nominal power for the whole range of operation) in order to follow the voltage set-points established by the TSO. At the moment, in Spain, wind farms do not have to provide this service of voltage control but must control output power factor in order to support voltage control by working with leading power factor in high demand periods, lagging power factor in low demand periods and unity power factor in regular demand periods. By achieving the required power factor a rewarding is obtained.

In any case, wind farm power factor control also requires knowing the wind turbine generator reactive power capability in order to plan the reactive power resources to achieve the required power factor. Taking into account that the doubly fed asynchronous generator (DFAG) is the most employed generator in wind energy generation nowadays, this paper studies the power capability curve of DFAG using a similar approach to the one used in synchronous generators.

2. Mathematical model

Fig. 1 represents the single-phase equivalent circuit of a doubly fed asynchronous generator in steady state. The stator and rotor equations derived from this equivalent circuit are

$$\vec{U}_S = -R_S\vec{I}_S - jX_S\vec{I}_S - jX_M\vec{I}_R, \qquad \vec{U}_R = -R_R\vec{I}_R - jsX_R\vec{I}_R - jsX_M\vec{I}_S \quad (1)$$

where U_S is the stator voltage, U_R the rotor voltage, I_S the stator current, I_R the rotor current, R_S the stator resistance, R_R the rotor resistance, X_S the stator reactance, X_R the rotor reactance, X_M the mutual reactance, and s is the slip.

Being slip the ratio between rotor to stator pulsation:

$$s = \frac{\omega_r}{\omega_s} \quad (2)$$

By defining the generator internal emf as

$$\vec{E} = -jX_M\vec{I}_R \quad (3)$$

and substituting (3) into the stator equation in (1):

$$\vec{U}_S = -R_S\vec{I}_S - jX_S\vec{I}_S + \vec{E} \quad (4)$$

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0378-7796/$ – see front matter © 2008 Published by Elsevier B.V.
doi:10.1016/j.epsr.2008.02.007

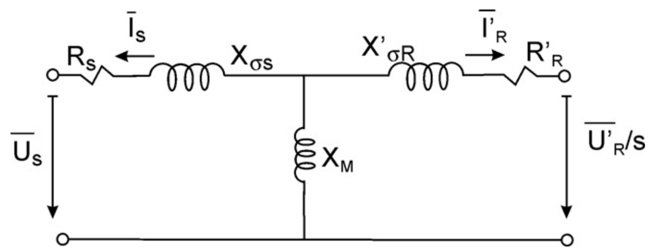

Fig. 1. Doubly fed asynchronous generator equivalent circuit.

The stator equation (4) can be represented by an equivalent circuit as shown in Fig. 2.

This circuit is identical to the synchronous generator classical equivalent circuit.

2.1. Stator active and reactive power

Stator active and reactive power can be obtained as follows:

$$P_S + jQ_S = 3\vec{U}_S\vec{I}_S^* \tag{5}$$

From the equivalent circuit, neglecting stator resistance:

$$\vec{I}_S = \frac{\vec{E} - \vec{U}_S}{jX_S} \tag{6}$$

Introducing (6) into (5) and separating into real and imaginary parts:

$$P_S = 3\frac{1}{X_S}EU_S\sin\delta, \qquad Q_S = 3\frac{1}{X_S}EU_S\cos\delta - 3\frac{U_S^2}{X_S} \tag{7}$$

where U_S and E are the rms value of the stator voltage and internal emf vectors, respectively, and δ is the angle between both vectors (see vector diagram in Fig. 3).

2.2. Rotor active and reactive power

Rotor active and reactive power can be obtained as

$$P_R + jQ_R = 3\vec{U}_R\vec{I}_R^* \tag{8}$$

From rotor equation in (1) and taking into account (3), (5) and (6):

$$P_R + jQ_R = 3\left[-R_RI_R^2 - jsX_RI_R^2 + js\frac{1}{X_S}(\vec{E} - \vec{U}_S)\vec{E}^*\right] \tag{9}$$

Separating (9) into real and imaginary parts and neglecting rotor resistive losses:

$$P_R = -s3\frac{1}{X_S}EU_S\sin\delta, \qquad Q_R = -s\left(3X_RI_R^2 + 3\frac{1}{X_S}EU_S\cos\delta - 3\frac{E^2}{X_S}\right) \tag{10}$$

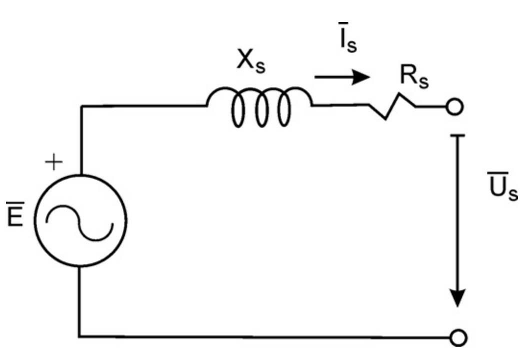

Fig. 2. Stator equivalent circuit.

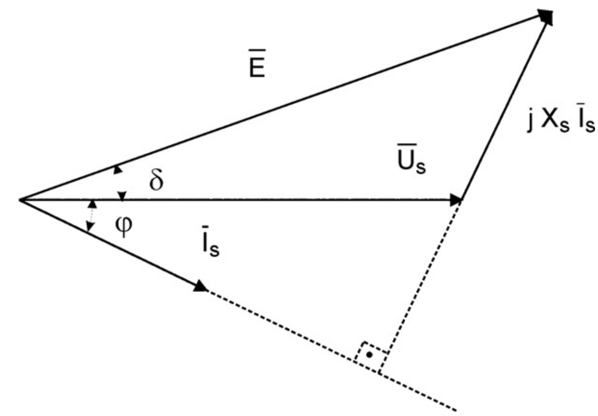

Fig. 3. Stator vector diagram.

2.3. Total active and reactive power

The doubly fed asynchronous generator converts the wind turbine mechanical power into electrical power that is fed into the grid through the stator and through the rotor by means of a frequency converter consisting of two back to back inverters (Fig. 4).

From (7) and (10):

$$P_R = -sP_S \tag{11}$$

This equation shows that, working the machine as generator ($P_S > 0$), rotor power is positive when slip is negative, i.e., rotor power is fed into the grid when the generator is working at super-synchronous speed; and rotor power is negative when slip is positive, i.e., rotor power is drawn from the grid when the generator is working at sub-synchronous speed. This shows that the frequency converter connected between the rotor circuit and the grid must be bidirectional in order to allow both the super-synchronous and sub-synchronous operation of the generator.

The rotor speed is controlled through the generator torque in order to achieve maximum power for the incoming wind. The generator torque is controlled by means of FOC [3,4] or DTC [5] techniques, which impose the required rotor frequency and voltage by means of the rotor connected inverter.

Total power fed into the grid is

$$P_T = P_S + P_R \tag{12}$$

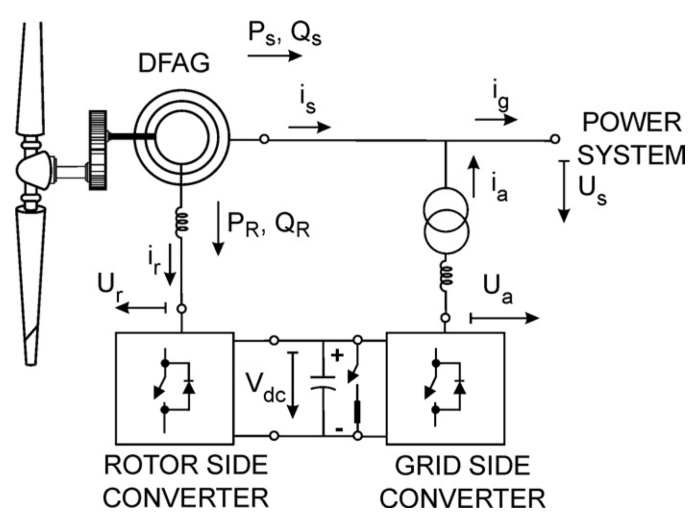

Fig. 4. DFAG configuration.