Renewable Energy 50 (2013) 177–187

Contents lists available at SciVerse ScienceDirect

Renewable Energy

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

A survey of shaft voltage reduction strategies for induction generators in wind energy applications

M. Ebrahim Adabi*, Abolfazl Vahedi

Electrical Engineering, Iran University of Science and Technology, Center of Excellence for Power System Automation and Operation, Tehran, Iran

A R T I C L E I N F O

Article history:
Received 28 November 2011
Accepted 12 June 2012
Available online 20 July 2012

Keywords:
Shaft voltage
Common mode voltage(CMV)
SCIG
DFIG
Wind turbine
PWM

A B S T R A C T

Common mode voltage generated by PWM inverters and the parasitic couplings of the machine structure in high frequencies create a model for the system which leads to an induced voltage on the shaft. Shaft voltage became a dominant side effect of power electronic converters since they are widely used in wind turbine applications to prepare desirable frequency and suitable control on active and reactive power. This voltage is known as the main cause of many unwanted problems such as leakage current, ball-bearings damages and reduction of generator's life time. In this paper, pulse width modulation strategies have been presented for two-level and three-level back-to-back AC–DC–AC converters in order to reduce or eliminate common mode voltage of these converters for reduction or elimination of shaft voltage in squirrel cage and doubly fed induction generators. Applying these techniques lead to complete elimination of shaft voltage for squirrel cage Induction generator with back to back AC/DC/AC converter and a 66 percent reduction of the shaft voltage generation in the Doubly Fed Induction Generator. Simulation results and mathematical analysis have been presented to investigate proposed techniques.

1. Introduction

Due to lack of the traditional energy resources and their upcoming cost challenges, renewable energy resources such as wind, solar and fuel cells became key player elements. Among these resources, wind energy has been widely accepted in power industry as a result of its cleanness, easy to access, proficiency and cost effectiveness in world energy paradigm [1]. Natural changes of the wind mechanical power lead to a variable turbine speed and a variable output voltage. This problem can be avoided by using mechanical solutions such as gear boxes to adjust the speed. Power electronics converters and control modules are also used to achieve an adjustable output voltage in terms of frequency and magnitude [2]. To achieve a variable speed constant frequency system, an induction generator is considered attractive due to its flexible rotor speed characteristics with respect to the constant stator frequency [3,4].

First built wind turbines were at the range of KW and they reached to MW range nowadays, therefore wind energy generation got a dominant role in power generation. Squirrel cage induction generators were the first generators used in wind turbines. These generators are directly connected to the grid and there were no control on active and reactive power and frequency of the system. When the range of power generation increased, controlling these parameters became more important. By using power electronic devices induction generators can act both in constant and variable speed [5].

Three main types of induction generators which are used in wind energy generation systems are:

- Squirrel cage induction generator which can be connected directly to the grid or via power electronic converter to have the capability of acting in variable speed.
- Wound rotor induction generator which controls the speed by changing rotor resistance.
- Doubly fed induction generator which prepares various range for speed change up to 30%.

Since wind turbine acts in a variable rotational speed, electrical frequency of the generator changes, therefore it should be separated from grid frequency. This can be done by means of power electronic converters [6]. When the switching frequency of these converters increased, some problems have been occurred which have been previously seen in waveguide instruments like antennas and radio signal equipments [7]. The effects of high frequency components of the voltage which is generated through PWM techniques are usually

* Corresponding author. Tel.: +98 911 7897168.
E-mail addresses: ebrahimadabi@gmail.com (M.E. Adabi), a.vahedi@iust.ac.ir (A. Vahedi).

0960-1481/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.renene.2012.06.026

neglected in electromechanical analysis of the AC machine. There are many capacitance couplings in the generator structure that could be neglected in low frequency analysis, but the situation is completely different in high frequency [8].

By applying PWM in three phase inverter, a voltage will be generated between neutral point of the load and the ground which is known as CMV. This voltage acts as a source for many unwanted problems in motor drives such as shaft voltage and bearing current due to parasitic capacitances which exist in the structure of the machine [9]. According to the analysis of [10], a high percentage of CMV generated by rotor side converter in a DFIG converts to shaft voltage. This amount is much greater than IEC-34-17 standard which is a harmful phenomena and leads to both safety and maintenance problems. Therefore, CMV is an important factor in high frequency modeling of electrical machines and is the main source of shaft voltage in generator structure because of small parasitic capacitances. PWM techniques that reduce or eliminate CMV would be a suitable and cheap solution which will be greatly fascinated in industry [11].

SCIG and DFIG applications in wind turbine system are discussed in Section (2) and also DC balancing and active and reactive power control in DFIG system is studied in this section as well. Generated CMV and PWM strategies for its reduction in two-level and three level converters are given in Section (3). Section (4) gives calculations of shaft voltage and its remediation strategies for both SCIG and DFIG. Simulation results of proposed PWM technique for shaft voltage reduction of DFIG in MATLAB wind turbine system are shown in Section (5).

2. Induction generators in wind energy applications and their power control approaches

2.1. Squirrel cage induction generator (SCIG)

Fig. 1 shows the structure of stator fed Squirrel cage induction generator in which stator is directly connected to the grid through back to back AC/DC/AC convertor. In this structure generator side convertor controls the active power and grid side convertor controls reactive power.

For above topology, back to back convertor should operate in nominal power of the generator; this would be considered as the main drawback of this system due to increasing the cost of power electronic convertor [12].

2.2. Doubly fed induction generator (DFIG)

Fig. 2 shows the structure of DFIG. In DFIG, stator is directly connected to the grid while rotor is connected through a back to back AC/DC/AC convertor [13]. This topology has got various applications in variable speed wind turbines recently. The main benefit of this system is that power electronic convertors contain 20–30 percent of total power, therefore the loss and cost of the inverter decrease [14–16].

If rotor rotates above synchronous speed, power would be delivered from both rotor and stator side to the grid. The main principle of rotor side convertor is controlling active and reactive power and grid side convertor has the duty of DC link voltage balancing [17].

2.2.1. Active and reactive power control

As mentioned in above section the main duty of rotor side converter is to control active and reactive power. From generator equation, stator and rotor flux would be achieved as equation below:

$$\begin{aligned} I_sR_s + V_s &= -\frac{d\psi_s}{dt} - j\omega\psi_s; \qquad \psi_s = L_sI_s + L_mI_r \\ I_rR_r + V_r &= -\frac{d\psi_r}{dt} - j\left(\omega_1 - \omega_r\right)\psi_r; \qquad \psi_r = L_rI_r + L_mI_s \end{aligned} \tag{1}$$

By considering stator flux aligned d-axis, the equations of voltage, current and flux are given as:

$$\begin{aligned} I_dR_s + V_d &= -\frac{d\psi_d}{dt} \\ I_qR_s + V_q &= -\omega_r\psi_q \end{aligned} \tag{2}$$

By neglecting from stator resistance $(R_s = 0)$ and assuming constant value for stator flux $\left(\frac{d\psi_d}{dt} = 0\right)$:

$$\begin{aligned} V_d &= 0 \\ V_q &= -\omega_r\psi_q \end{aligned} \tag{3}$$

Finally the active and reactive power of the stator is given as equation bellow:

$$\begin{aligned} &P_s \approx \frac{3}{2}\left(V_dI_d + V_qI_q\right) = \frac{3}{2}V_qI_q = \frac{3}{2}\omega_1 \; \psi_d \cdot \frac{L_mI_{qr}}{L_s}; \quad \omega_1 = \omega_r \\ &Q_s \approx \frac{3}{2}\left(V_dI_q - V_qI_d\right) = \frac{3}{2}\omega_1 \; \psi_dI_d = \frac{3}{2}\omega_1 \; \frac{\psi_d}{L_s}\left(\psi_d - L_mI_{dr}\right); \\ &\omega_1 = \omega_r \end{aligned} \tag{4}$$

As it can be seen from Equation (4), the output active and reactive power of the stator can be controlled through i_{qr} and i_{dr} which are the currents of the rotor in q and d-axis respectively [18].

2.2.2. DC-link voltage control

Fig. 3 shows the schematic of grid side converter.

With respect to above figure, voltage is given as equation below:

$$\begin{vmatrix} V_a \\ V_b \\ V_c \end{vmatrix} = R\begin{vmatrix} I_{as} \\ I_{bs} \\ I_{cs} \end{vmatrix} + L\frac{d}{dt}\begin{vmatrix} I_{as} \\ I_{bs} \\ I_{cs} \end{vmatrix} + \begin{vmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{vmatrix} \tag{5}$$

By transferring above equation from abc to d-q space:

$$\begin{aligned} V_d &= Ri_{ds} + L\frac{di_{ds}}{dt} - \omega_1Li_{qs} + V_{ds} \\ V_q &= Ri_{qs} + L\frac{di_{qs}}{dt} + \omega_1Li_{ds} + V_{qs} \end{aligned} \tag{6}$$

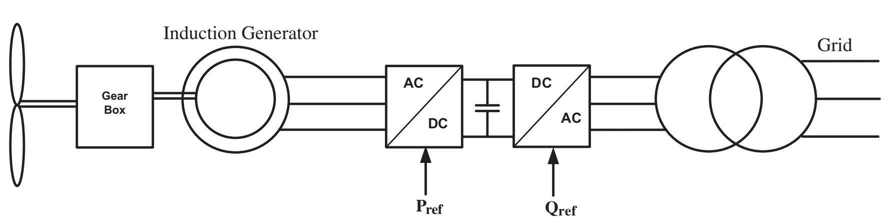

Fig. 1. Structure of stator fed squirrel cage induction generator.