Minimization of Torque Ripple for a Doubly Fed Induction Generator in Medium Voltage Wind Power System under Unbalanced Grid Condition

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Abstract

This paper investigates control algorithms for a doubly fed induction generator(DFIG) with a back-to-back three-level neutral-point clamped voltage source converter in medium voltage wind power system under unbalanced grid conditions. Two different control algorithms to compensate for unbalanced conditions are proposed. Evaluation factors of control algorithm are fault ride-through(FRT) capability, efficiency, harmonic distortions and torque pulsation. Zero regulated negative sequence stator current control algorithm has the most effective performance concerning FRT capability and efficiency. Ripple-free control algorithm nullifies oscillation component of active power and reactive power. Ripple-free control algorithm shows the least harmonic distortions and torque pulsation. Combination of zero regulated negative sequence stator current and ripple-free control algorithm control algorithm depending on the operating requirements and depth of grid unbalance presents the most optimized performance factors under the generalized unbalanced operating conditions leading to high performance DFIG wind turbine system.

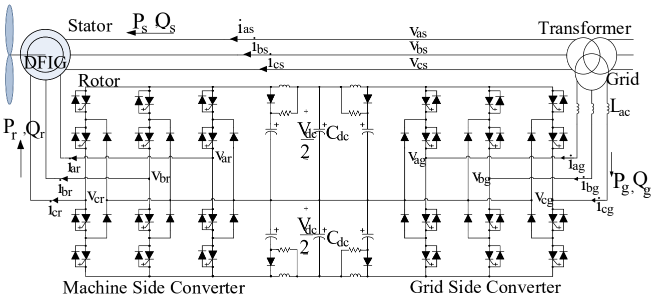

Fig. 1 Overall scheme of DFIG wind turbine with a back-to-back three-level NPC voltage source converter

1. Introduction

Wind power installation has been increasing both in number and size of individual wind turbine unit. Doubly Fed Induction Generator (DFIG) is widely used as wind generator due to its economic requirement of power converter in rotor side. The structure of DFIG wind power system with a back-to-back three-level NPC voltage source converter is described in Fig 1.

Because of the direct connection between the stator and grid, the unbalanced grid voltage causes unbalanced stator currents. The unbalanced currents generate unequal heating of the stator windings and oscillations of torque and output power resulting in a mechanical stress on the drive train and gearbox as well as adverse acoustic noise [1].

The control methods of the Grid Side Converter (GSC) to eliminate input power oscillations at the grid side of rotor under unbalanced input supply have been investigated in past few years. In [2], Suh and Lipo have proposed a method to directly control the instantaneous active power at the poles of the rectifier. The control method in [2] can achieve effective elimination of the oscillations under unbalanced operating conditions.

Control of the Machine Side Converter (MSC) in DFIG wind power system with back-to-back converter to reduce torque pulsation by compensating the rotor current under unbalanced grid voltage has been studied in past few years. Control method to reduce torque pulsation and rotor current harmonics by compensating negative sequence components utilizing either GSC or MSC was developed in [3]. In [4], control methods to eliminate pulsations of torque using MSC and to compensate oscillation of active and reactive power and current of stator were presented.

In this paper, three different unbalance compensating control algorithms are compared for the medium-voltage wind power system using DFIG equipped with a back-to-back three-level NPC voltage source converter. The problems generated by unbalanced grid conditions such as overcurrent of stator and rotor, active and reactive power ripples of stator, torque pulsation at the shaft, and degradation of THD of line currents are evaluated. Using the control laws addressed in [2] and [5], the key performance factors of FRT capability, efficiency, torque pulsation and harmonic distortion of stator current are investigated with respect to each control algorithm. The cost-effective and most-optimized control algorithm suitable for DFIG in medium-voltage wind power system is proposed in this paper.

2. Dynamic Model of DFIG under Unbalanced Conditions

2-1. DFIG model under unbalanced conditions

Under unbalanced grid voltage, DFIG can be effectively modeled by using both positive and negative sequence components of voltages and currents. The positive and negative sequence components for the voltages of stator and rotor in a synchronous rotating frame are expressed as followings.

$$V_{dqs}^{p} = R_s I_{dqs}^{p} + L_s\left(\frac{d}{dt} I_{dqs}^{p} + j\omega I_{dqs}^{p}\right) + L_m\left(\frac{d}{dt} I_{dqr}^{p} + j\omega I_{dqr}^{p}\right) \tag{1}$$

$$V_{dqr}^{p} = R_r I_{dqr}^{p} + L_r\left(\frac{d}{dt} I_{dqr}^{p} + j(\omega - \omega_r) I_{dqr}^{p}\right) + L_m\left(\frac{d}{dt} I_{dqs}^{p} + j(\omega - \omega_r) I_{dqs}^{p}\right) \tag{2}$$

$$V_{dqs}^{n} = R_s I_{dqs}^{n} + L_s\left(\frac{d}{dt} I_{dqs}^{n} - j\omega I_{dqs}^{n}\right) + L_m\left(\frac{d}{dt} I_{dqr}^{n} - j\omega I_{dqr}^{n}\right) \tag{3}$$

$$V_{dqr}^{n} = R_r I_{dqr}^{n} + L_r\left(\frac{d}{dt} I_{dqr}^{n} - j(\omega + \omega_r) I_{dqr}^{n}\right) + L_m\left(\frac{d}{dt} I_{dqs}^{n} - j(\omega + \omega_r) I_{dqs}^{n}\right) \tag{4}$$

2-2. Instantaneous output active and reactive power

The instantaneous output active power of stator is obtained by taking the real part of the complex power [2].

$$p_s(t) = Re\{S_s\} = P_{so} + P_{sc2}\cos(2\omega t) + P_{ss2}\sin(2\omega t) \tag{5}$$

The instantaneous output reactive power can be developed based on a set of voltages lagging the input voltages by 90° [2]. A complex quantity, T_s referred as a quadrature complex power is defined and given in (6). The instantaneous output reactive power

q_s(t) is equivalent to the real part of T_s [2].

$$T_s = -\frac{3}{2} V^{s\,'}_{dqs} I^{s\,*}_{dqs} = -\frac{3}{2}(-je^{j\omega t}V^{p}_{dqs} + je^{-j\omega t}V^{n}_{dqs})(e^{j\omega t}I^{p}_{dqs} + e^{-j\omega t}I^{n}_{dqs})^{*} \qquad (6)$$

$$q_s(t) = Re\ \{T_s\} = Q_{so} + Q_{sc2}\ cos\ (2\omega t) + Q_{ss2}\ sin\ (2\omega t) \qquad (7)$$

2-3. Machine Side Converter Control

The MSC is controlled by applying the three different control algorithms to reduce torque pulsation,

Ripple-free control algorithm is achieved by nullifying oscillating components of the instantaneous output active power of stator as shown in (8). The rotor current reference values are calculated by using in (9).

$$P_{sc2} = 0,\ P_{ss2} = 0 \qquad (8)$$

$$-\frac{2}{3}\begin{pmatrix} P_{so} \\ Q_{so} \\ P_{ss2} \\ P_{sc2} \end{pmatrix} = \begin{pmatrix} -V^{p}_{ds} & -V^{p}_{qs} & -V^{n}_{ds} & -V^{n}_{qs} \\ -V^{p}_{qs} & V^{p}_{ds} & V^{n}_{qs} & -V^{n}_{ds} \\ -V^{n}_{qs} & V^{n}_{ds} & V^{p}_{qs} & -V^{p}_{ds} \\ -V^{n}_{ds} & -V^{n}_{qs} & -V^{p}_{ds} & -V^{p}_{qs} \end{pmatrix} \left(\frac{1}{\omega L_s} \begin{pmatrix} V^{p}_{qs} \\ -V^{p}_{ds} \\ -V^{n}_{qs} \\ V^{n}_{ds} \end{pmatrix} - \frac{L_m}{L_s} \begin{pmatrix} I^{p}_{dr} \\ I^{p}_{qr} \\ I^{n}_{dr} \\ I^{n}_{qr} \end{pmatrix} \right) \qquad (9)$$

Zero regulated negative sequence stator current control algorithm is similar to the ripple-free control algorithm except that the negative sequence components of stator current (I^{n}_{ds} and I^{n}_{qs}) are set to zero values as shown in (10).

$$I^{n}_{ds} = (-\frac{1}{\omega L_s}V^{n}_{qs} - \frac{L_m}{L_s}I^{n}_{dr}) = 0, \qquad I^{n}_{qs} = (\frac{1}{\omega L_s}V^{n}_{ds} - \frac{L_m}{L_s}I^{n}_{qr}) = 0 \qquad (10)$$

In the single-frame control algorithm, the three-phase switching modulation functions of machine side converter (S_a,S_b, and S_c) are set to be balanced in a single-frame controller as shown in (11). This means that the negative sequence components of rotor current (I^{n}_{dr}, and I^{n}_{qr}) cannot be regulated thereby resulting in uncontrolled values.

$$V^{n}_{dr} = 0\ ,\ V^{n}_{qr} = 0 \qquad (11)$$

3. Comparison of Three Control Algorithms

Three different control algorithms are compared with respect to four performance factors; FRT capability, efficiency, harmonic distortions and torque pulsation. The simulation is made based on the operating condition specified in Table I. The result is obtained under the single-phase under-voltage unbalance condition.

TABLE I
Parameters of DFIG Wind Power System

Parameter	Value	Parameter	Value
Rated power(MW)	1.5	Stator resistance(mΩ)	14
Rated voltage(line)(V)	575	Rotor resistance(mΩ)	0.992
Frequency(Hz)	50	Stator leakage inductance(μH)	89.98
Inertia(kg m^2)	5	Rotor leakage inductance(μH)	82.09
Pole pairs	2	Magnetizing inductance(mH)	1.53
Rated wind speed(m/s)	12	DC link capacitance(mF)	76

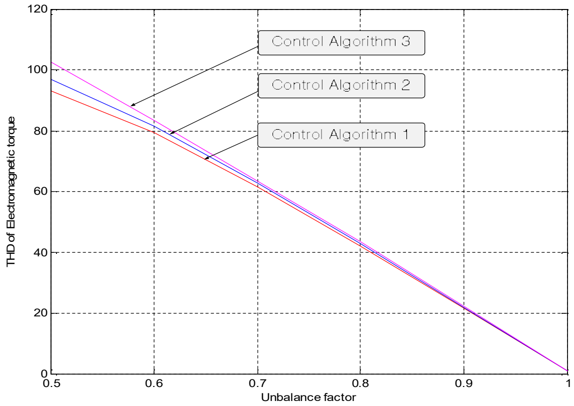

Fig. 2 Torque pulsation generated

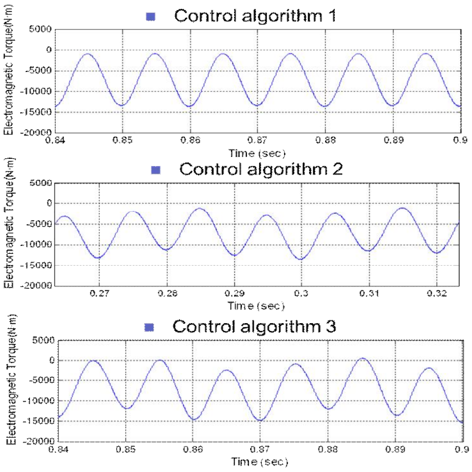

Fig. 3 Torque pulsation waveform under UF=0.5

The zero regulated negative sequence stator current control algorithm is favored as having the smallest amplitude of peak rotor current. Zero regulated negative sequence stator current control algorithm outperforms the other two methods.

Ripple-free control algorithm generates the least amount of harmonic distortions in both stator current and dc link voltage. Ripple-free control algorithm provides the most effective result about the reduced torque pulsation as shown in Fig. 2.

4. Conclusion

This paper investigates unbalance compensating control algorithms for a doubly fed induction wind generator employing a back-to-back three-level NPC voltage source converter. The converter along with DFIG is modeled based on the symmetrical components and dq synchronous frames under unbalanced grid conditions. Three different control algorithms have been devised based on instantaneous output active and reactive power of stator. These algorithms are compared with respect to FRT capability, efficiency, harmonic distortions and torque pulsation. Zero regulated negative sequence stator current control algorithm having negative sequence stator components set to zero shows the most optimized and cost-effective performance in terms of fault ride-through capability and efficiency aspects. Ripple-free control algorithm that nullifies the oscillating components of the instantaneous active power surpasses the other two algorithms regarding harmonic distortion factor and torque pulsation. By combining these two algorithms depending on the depth of grid unbalance, four performance factors such as FRT capability, efficiency, harmonic distortions, and torque pulsation can be improved under the generalized unbalanced grid conditions leading to high performance DFIG wind turbine system.

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