Control Strategy of Improved Transient Response for a Doubly Fed Induction Generator in Medium Voltage Wind Power System under Grid Unbalance

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ABSTRACT

This paper investigates control algorithms for a doubly fed induction generator with a back-to-back three-level neutral-point clamped voltage source converter in medium voltage wind power system under unbalanced grid conditions. Control algorithms to compensate for unbalanced conditions have been investigated with respect to four performance factors; fault ride-through capability, instantaneous active power pulsation, harmonic distortions, and torque pulsation. The control algorithm having zero amplitude of torque ripple shows the most cost-effective performance concerning torque pulsation. The least active power pulsation is produced by control algorithm that nullifies the oscillating component of the instantaneous stator active and reactive power. Combination of these two control algorithms depending on the operating requirements and depth of grid unbalance presents most optimized performance factors under the generalized unbalanced operating conditions leading to high performance DFIG wind turbine system. The proposed control algorithms are verified through transient response in the simulation.

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.

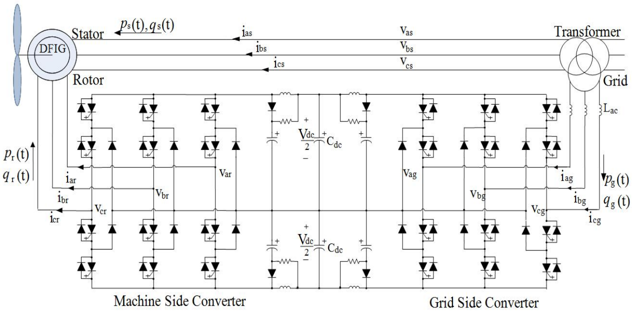

Fig 1 Overall scheme of DFIG wind turbine with a back-to-back three-level NPC voltage source converter

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, stator active power pulsation, 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.

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

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

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

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

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].

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

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].

$$T_s = -\frac{3}{2} V_{dqs}^{s\,'} I_{dqs}^{s\,*} = -\frac{3}{2}\left(-je^{j\omega t} V_{dqs}^{p} + je^{-j\omega t} V_{dqs}^{n}\right)\left(e^{j\omega t} I_{dqs}^{p} + e^{-j\omega t} I_{dqs}^{n}\right)^{*} \quad (6)$$

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

2.3 Control Algorithms

Three algorithms to be investigated in this paper are ripple-free stator power control algorithm, zero torque ripple control algorithm, and single-frame control algorithm.

Ripple-free stator power 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).

$$P_{ss2} = 0,\ P_{sc2} = 0 \tag{8}$$

$$\begin{bmatrix} P_{so} \\ Q_{so} \\ P_{ss2} \\ P_{sc2} \end{bmatrix} = \frac{3}{2}\begin{bmatrix} -V_{ds}^{p} & -V_{qs}^{p} & -V_{ds}^{n} & -V_{qs}^{n} \\ -V_{qs}^{p} & V_{ds}^{p} & V_{qs}^{n} & -V_{ds}^{n} \\ -V_{qs}^{n} & V_{ds}^{n} & V_{qs}^{p} & -V_{ds}^{p} \\ -V_{ds}^{n} & -V_{qs}^{n} & -V_{ds}^{p} & -V_{qs}^{p} \end{bmatrix} \left[\frac{1}{\omega L_s}\begin{bmatrix} V_{qs}^{p} \\ -V_{ds}^{p} \\ -V_{qs}^{n} \\ V_{ds}^{n} \end{bmatrix} - \frac{L_m}{L_s}\begin{bmatrix} I_{dr}^{p} \\ I_{qr}^{p} \\ I_{dr}^{n} \\ I_{qr}^{n} \end{bmatrix} \right] \tag{9}$$

Zero torque ripple control algorithm is designed to minimize the ripple of torque at the shaft of wind turbine as shown in (10). In a similar manner as in CA1, the positive and negative sequential components of rotor current ($I_{dr}^{p}, I_{qr}^{p}, I_{dr}^{n}$ *and* I_{qr}^{n}) can be calculated from four control laws based on (11).

$$P_{ems2} = 0,\ P_{emc2} = 0 \tag{10}$$

$$\begin{bmatrix} P_{em0} \\ \hat{Q}_{so} \\ P_{ems2} \\ P_{emc2} \end{bmatrix} = \frac{3L_m\omega_r}{2L_s\omega}\begin{bmatrix} V_{ds}^{p} & V_{qs}^{p} & -V_{ds}^{n} & -V_{qs}^{n} \\ \frac{\omega}{\omega_r}V_{qs}^{p} & -\frac{\omega}{\omega_r}V_{ds}^{p} & -\frac{\omega}{\omega_r}V_{qs}^{n} & \frac{\omega}{\omega_r}V_{ds}^{n} \\ -V_{qs}^{n} & V_{ds}^{n} & -V_{qs}^{p} & V_{ds}^{p} \\ -V_{ds}^{n} & -V_{qs}^{n} & V_{ds}^{p} & V_{qs}^{p} \end{bmatrix}\begin{bmatrix} I_{dr}^{p} \\ I_{qr}^{p} \\ I_{dr}^{n} \\ I_{qr}^{n} \end{bmatrix} \tag{11}$$

Single-frame control algorithm has only one current regulator for positive sequence components of rotor currents (I_{dr}^{p} and I_{qr}^{p}). The three-phase switching modulation functions and pole voltages of machine side converter (v_{ar}, v_{br}, and v_{cr}) are set to be balanced in a single-frame controller as shown in (12).

$$V_{dr}^{n} = 0,\ V_{qr}^{n} = 0 \tag{12}$$

3. Comparison of Control Algorithms

Three different control algorithms are compared with respect to four performance factors; FRT capability, stator active power pulsation, harmonic distortions, and torque pulsation. The simulation is made based on the operating condition specified in Table I. The result is obtained under the grid voltage of 50% single-phase unbalance.

Ripple-free stator power control algorithm produces the least amount of harmonic component of instantaneous active and reactive power among all three control algorithms as shown in Fig. 2.

Zero torque ripple control algorithm has the most effective result about the reduced torque pulsation and transient rotor peak current as shown in Fig. 3 and Table II.

TABLE I
Parameters of DFIG Wind Power System

Parameter	Value	Parameter	Value
Rated power(MW)	1 5	Stator resistance(mΩ)	1 4
Rated voltage(line)(V)	575	Rotor resistance(mΩ)	0 992
Frequency(Hz)	50	Stator leakage inductance(μH)	89 98
Inertia(kg m^2)	25	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

TABLE II
Performance Factors of Each Control Algorithm

Factors	CA 1	CA 2	CA 3
Stator active power ripple at 100Hz	1 kW	465 kW	362 kW
Torque ripple at 100Hz	2732 N m	11 N m	4409 N m
Transient peak rotor current	2748 A	2957 A	3255 A
THD of stator current	6 7 %	5 6 %	10 8 %

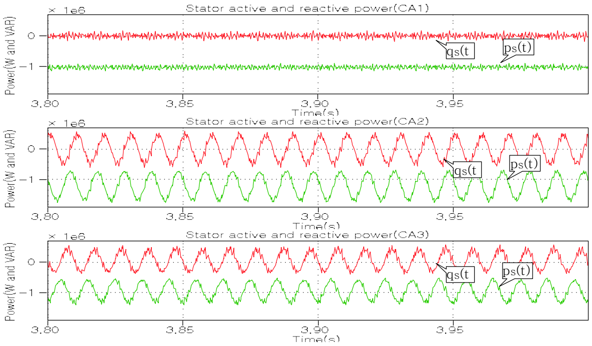

Fig 2 Instantaneous active and reactive power of stator (UF=0 5)

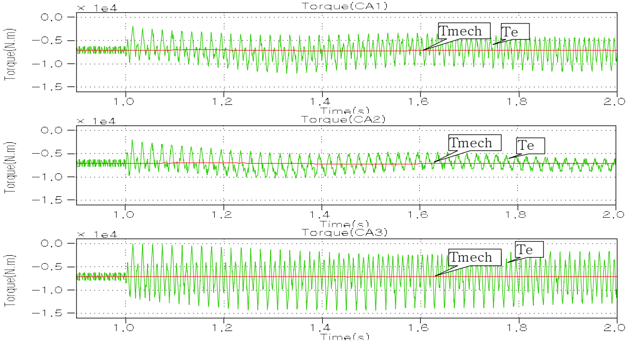

Fig 3 Electromagnetic torque from DFIG and mechanical torque from blade (UF=1 to 0 5 at 1sec)

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. Three different control algorithms have been devised based on instantaneous output active, reactive power of stator, and torque. These algorithms are compared with respect to FRT capability, stator active power ripple, harmonic distortions, and torque pulsation. Control algorithm 2 having torque ripple set to zero shows the most optimized and cost-effective performance in terms of torque pulsation. Control algorithm 1 that nullifies the oscillating components of the instantaneous stator active power surpasses the other two algorithms regarding stator active power pulsation. By combining control algorithm 1 and 2 depending on the depth of grid unbalance, four performance factors such as FRT capability, stator active power pulsation, harmonic distortions, and torque pulsation can be improved under the generalized unbalanced grid conditions leading to high performance DFIG wind turbine system. The proposed control algorithms are verified through transient response in the simulation.

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