Control of Doubly Fed Induction Generator under Unbalanced Voltages for Reduction of Torque Pulsation

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Received: June 17, 2010 / Accepted: October 30, 2010 / Published: March 31, 2011.

Abstract: The unbalanced voltages cause negative effects on the doubly fed induction generator (DFIG) such as torque pulsation and increased stator current. Based on the symmetrical component theory, the torque pulsation is the consequence of the interaction of stator and rotor currents of different sequences. This paper presents a control technique to reduce the effect of unbalanced voltages on the DFIG in wind energy conversion systems. The negative sequence stator voltage is derived from the unbalanced three phase stator voltages. The compensated rotor voltage in terms of the derived negative sequence stator voltage and slip which minimizes the negative stator and rotor currents is proposed. The results from the simulation of control system with steady state model and dynamic model of the DFIG show that additional control loop with compensated voltage can significantly reduce torque and reactive power pulsations.

Key words: Doubly fed induction generator (DFIG), unbalanced voltages, symmetrical components.

Nomenclature

- $\dot{I}_{Ms}$: Stator magnetizing current
- $\dot{I}_{R+}$, $\dot{I}_{R-}$: Positive and negative sequence components of RMS rotor current phasors
- $\dot{I}_{S+}$, $\dot{I}_{S-}$: Positive and negative sequence components of RMS stator current phasors
- $i_{Rd}$, $i_{Rq}$: d and q axis rotor current symmetrical components in synchronous reference frame
- $i_{Sd}$, $i_{Sq}$: d and q axis stator current symmetrical components in synchronous reference frame
- $L_{m}$, $X_{m}$: Magnetizing inductance and reactance
- $L_{R}$, $X_{R}$: Rotor inductance and reactance.
- $L_{S}$, $X_{S}$: Stator inductance and reactance
- $X_{ce}$, $X_{cr}$: Stator and rotor leakage reactance
- $P$: Number of magnetic poles
- $R_{S}$, $R_{R}$: Stator and rotor winding resistances
- $S$: Slip
- $T_{e}$: Electrical torque
- $\dot{U}_{S+}$, $\dot{U}_{S-}$: Positive and negative sequence components of phase voltage
- $\dot{U}_{S}$, $\dot{U}_{S}$: Rotor and stator voltages
- $u_{Rd}$, $u_{Rq}$: Time varying rotor voltage and current vectors
- $u_{Sd}$, $u_{Sq}$: Time varying stator voltage and current vectors
- $\mu$: Stator field current angle
- $\sigma$: Total leakage factor
- $\sigma_{S}$: Stator leakage factor
- $\epsilon$: Rotor angle
- $\omega$: Stator line voltage frequency
- $\omega_{mS}$: Instantaneous angle speed of stator field current

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1. Introduction

Wind energy has been recognized as a sustainable source of energy and experienced rapid growth due to the technological development of wind turbines. Such development has led to a considerable decrease in cost and therefore allowed wind energy source to compete with conventional energy for electricity production. Many large wind farms employ doubly fed induction generator (DFIG) with variable speed wind turbines [1]. The DFIG-based wind turbines have several advantages such as variable speed control, four-quadrant active and reactive power operation. Moreover, converter rating is only 20-30% of generator rating which results in low power loss at the converter.

For a DFIG-based wind turbine, its stator side is directly connected to the grid whereas its rotor side is connected via two converters, as shown in Fig. 1. Two back-to-back variable frequency power converters, with a DC link, connect the rotor winding terminal of the DFIG to the 3-phase supply. In order to cover a wide operation range from sub-synchronous to super-synchronous speeds, these power converters must be able to operate with bi-directional flow of power. The converter which is connected to the rotor of the DFIG, is called machine side converter, whereas the converter connected to the AC supply, is called line side converter. The objective of the machine side converter is to control speed or stator active power and reactive power of the DFIG independently. The reference speed or active power is provided for maximum power extraction from wind energy. The objective of the line side converter during normal operation is to regulate the DC bus voltage at the reference value for both directions of rotor power flow and to operate at unity power factor.

Wind turbines are usually located in rural area or connected to a weak grid system. In that system, the unbalance of the grid voltage may arise even during normal operation. The unbalanced voltages are caused by, for example, unbalanced loads, large single-phase loads, untransposed lines. Severe voltage unbalance can be the result of unbalanced faults. The unbalanced voltage condition introduces many negative effects to the performance of 3-phase DFIG. This condition will cause unbalanced currents in the stator and rotor circuits and a small unbalanced voltage can cause a large unbalanced current. These effects create a pulsating torque with a twice frequency of that of the grid supply speed fluctuation, acoustic noise, and consequently, increased losses and reduced insulation life. The negative effects may be acceptable in small machines but not in larger ones. The pulsating torque causes fatigue in the rotor shaft, gearbox and other wind turbine mechanical parts.

Although a conventional proportional and integral (PI) control system can reduce unbalanced voltage to some extent, its effects are not significant. As a result, a number of methods to reduce the unbalanced effect have been proposed. One of these methods is based on an analysis of unbalanced operation of 3-phase machine with the symmetrical components, which states that the total voltage of any phase is equal to the sum of the corresponding components of the different sequences in that phase [2]. The set of symmetrical components is classified as positive, negative and zero-sequence components. Because the neutral point of a DFIG is, in general, not grounded, its zero sequence component does not exist. With the symmetrical components, the positive-sequence network and negative sequence network of the system can be derived and they are similar to the equivalent circuit of the balanced 3-phase system. The unbalanced condition will determine the equivalent circuit of the unbalanced system which is a combination of the
positive and negative sequence networks. The negative sequence current is the main cause for the negative effects from the unbalanced operation of DFIG.

Techniques for the reduction of pulsating torque and balancing the stator current have been introduced in some literatures. The positive and negative sequence of stator currents are calculated and separately controlled to limit the oscillation in instantaneous power and electrical torque [3]. An additional converter connected in series with the stator windings of the DFIG, which is called Series Grid-Side Converter (SGSC) is proposed for unbalanced voltage sag ride through capability [4]. During voltage sag, the SGSC compensates the positive and negative sequence components of the stator flux. The oscillation of stator active power reference is calculated and controlled with the information of power and torque estimation [5]. This action eliminates torque pulsation in direct power control method. The technique of network unbalance compensation using negative sequence current injection has been presented [6]. The required negative sequence current of DFIG, for grid voltage rebalancing control, can be provided by the machine side converter and line side converter.

The compensated rotor currents are added to the rotor currents to eliminate perturbation terms in magnetizing current [7]. A supplementary control loop is added to a conventional controller [8]. Separate control loops for positive and negative of rotor currents are suggested [9]. The control loop for negative sequence current is designed to reduce pulsating torque and reactive power. From these references, it can be assumed that the techniques for reducing the pulsation torque require additional control loop with complex mathematical operation.

This paper proposes a control method for DFIG under unbalanced grid voltages. The main control loops are the same as those of conventional controller. A compensated rotor voltage is derived from the unbalanced stator voltage and rotor speed. This compensated rotor voltage is directly combined to the reference rotor voltage from the main control system. No additional control loop with complex control operation is needed. The action minimizes the negative sequence component of the stator and rotor currents and hence reduces the oscillation in electromagnetic torque.

This paper is organized as follows: The definition of unbalanced voltage and current are described in Section 2. Section 3 explains the control of DFIG under balanced stator voltage condition. The mathematical model of DFIG under unbalanced stator voltage is derived in Section 4. The control method and the compensated rotor voltage for minimizing negative stator and rotor currents are proposed. The block diagram for the control of DFIG with unbalanced stator voltage operation is illustrated in this section. The effectiveness of the proposed method is verified in Section 5 for steady state model and in Section 6 for dynamic model. The conclusion is given in Section 7.

2. Definition of Unbalanced Voltage and Current

Three-phase voltages or currents are balanced or symmetrical if all the three phases have the same amplitude and a phase shift of 120° with respect to each other. If either or both of these conditions are not met, the system is said to be unbalanced or asymmetrical.

Based on the IEC standard [10], the unbalanced voltage is defined by the voltage unbalanced factor given by:

$$VUF (%) = \frac{V_2}{V_1} \cdot 100$$  \hspace{1cm} (1)

Similarly, the unbalanced current factor can be defined as:

$$CUF (%) = \frac{I_2}{I_1} \cdot 100$$  \hspace{1cm} (2)

where $V_1$ and $I_1$ are positive sequence components of voltage and current. $V_2$ and $I_2$ are negative sequence components of voltage and current.

3. Control of DFIG under Balanced Stator Voltage Condition

The control of DFIG through the machine side converter is based on field oriented control by
transforming 3-phase voltages and currents onto the synchronously rotating reference frame. The complex voltage and current vectors in the synchronously rotating reference frame are decomposed into two components namely $d$-axis component and $q$-axis component. In this case, the $d$-axis is assigned to coincide with the stator field axis and the $q$-axis is perpendicular to the $d$-axis in the direction of rotation. If the complex magnetizing current vector is aligned with the $d$-axis, the $q$-axis component of the magnetizing current in this reference frame would be zero. The magnetizing current or stator field current is defined as \[ i_{ms} = (1 + \sigma_s) i_{sf} + i_R e^{j\omega} = i_{ms} e^{j\theta} \] (3)

Based on this reference frame the torque equation is:

\[ T_s = -\frac{2P}{3} L_m (1 - \sigma) \sum_{n} r_n \] (4)

Apparently, the electromagnetic torque is proportional to the product of the $q$-axis component of rotor current and the stator magnetizing current. The stator magnetizing current, $i_{ms}$, corresponds to the main air gap flux which is constant at steady state. In addition, the stator reactive power can be determined as:

\[ q_s = \frac{2}{3} \omega_n L_m (1 - \sigma) (i_{fa} - i_{fa}) \] (5)

Eq. (5) shows that the $d$-axis rotor current can be used to control the stator reactive power. The stator power factor can be positive, negative or unity by controlling the reactive power in Eq. (5). Therefore, the electromagnetic torque and stator reactive powers can be controlled independently by manipulating the quadrature and direct components of the rotor current, respectively.

4. Mathematical Model of DFIG under Unbalanced Voltage

Based on the symmetrical components, time-varying stator voltage and current vectors in the stationary reference frame can be represented as the superposition of positive and negative sequence components \[11]\], as shown in Eqs. (6) and (7). The rotor current vector in stator coordinate can be expressed by Eq. (8).

\[ u_s = \frac{3}{2} \sqrt{2} (\dot{u}_{sa} e^{j\omega t} + \dot{u}_{sb} e^{j2\omega t}) = u_{sa} + u_{sb} \] (6)
\[ i_s = \frac{3}{2} \sqrt{2} (\dot{i}_{sa} e^{j\omega t} + \dot{i}_{sb} e^{j2\omega t}) = i_{sa} + i_{sb} \] (7)
\[ i_{z} = \frac{3}{2} \sqrt{2} (\dot{i}_{za} e^{j\omega t} + \dot{i}_{zb} e^{j2\omega t}) = i_{za} + i_{zb} \] (8)

As can be seen from Eqs. (6-8), the positive and negative component vectors rotate at the same angular velocity but in opposite direction. In steady state, if the synchronously rotating positive sequence is considered as a reference frame, the $d$-$q$ components of the positive sequence terms are constant while the negative sequence terms in this frame are alternating components with a frequency of $2\omega$. The torque equation is calculated from:

\[ T_s = \frac{3P}{2L_m} \sum_{n} \left[ \sum_{m} \left( \dot{u}_{sa} \dot{i}_{fa} + \dot{u}_{sb} \dot{i}_{fa} \right) \right] \] (9)

Substituting Eqs. (7) and (8) in Eq. (9),

\[ T_s = \frac{3P}{2L_m} \sum_{n} \left( i_{sa} i_{fa} - i_{sa} i_{fa} + i_{sb} i_{fa} - i_{sb} i_{fa} \right) \cos 2\omega t \] (10)

\[ + \left( i_{sa} i_{fa} - i_{sb} i_{fa} + i_{sa} i_{fa} - i_{sb} i_{fa} \right) \sin 2\omega t \]

Obviously from Eq. (10), the interaction between the stator and rotor currents of the same sequence produces a constant torque during steady state operation while the pulsating torque occurs due to the interaction between the stator and rotor currents of different sequences. The frequency of pulsating torque is $2\omega$. Consequently, the average torque is an algebraic sum of the two constant torques produced by the stator and rotor currents in the same sequence.

The DFIG stator and rotor voltage vectors in stationary reference frame can be mathematically expressed as:

\[ u_s = R_s i_s + L_s \frac{d}{dt} i_s + L_m \frac{d}{dt} \dot{i}_{za} e^{j\omega t} \] (11)
\[ u_z = R_s i_z + L_s \frac{d}{dt} i_z + L_m \frac{d}{dt} \dot{i}_{zb} e^{j2\omega t} \] (12)

In synchronously rotating reference frame, the stator and rotor voltage equations are illustrated in Eqs. (13-16) for both positive and negative sequence reference frames,

\[ u_{sa} = \left( R_s + L_s \frac{d}{dt} \dot{u}_{sa} \right) i_{sa} - \alpha \omega L_s i_{sa} + L_m \frac{d}{dt} \dot{i}_{sa} - \alpha \omega L_m i_{sa} \] (13)
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\[ u_{\text{sq}} = \omega L_d I_{\text{sq}} + \left( R_s + L_s \frac{d}{dt} I_{\text{sq}} + \omega L_m I_{\text{sd}} + L_m \frac{d}{dt} I_{\text{sd}} \right) \tag{14} \]

\[ u_{\text{dq}} = L_s \frac{d}{dt} I_{\text{dq}} - (\omega \pm \omega_m) L_{\text{d}} I_{\text{dq}} + (R_s + L_s) \frac{d}{dt} I_{\text{dq}} \]

\[ - (\omega \pm \omega_m) L_{\text{d}} I_{\text{dq}} + (R_s + L_s) \frac{d}{dt} I_{\text{dq}} \tag{15} \]

\[ u_{\text{qd}} = (\omega \pm \omega_m) L_{\text{d}} I_{\text{sd}} + L_m \frac{d}{dt} I_{\text{sd}} + (\omega \pm \omega_m) L_{\text{d}} I_{\text{sd}} \]

\[ + (R_s + L_s) \frac{d}{dt} I_{\text{sd}} \tag{16} \]

In steady state, the stator and rotor voltage equations of the positive and negative sequence systems in Eqs. (13-16) are written in forms of phasor equations by setting all the differential terms to be zero.

\[ \hat{U}_s = (R_s + jX_s) \hat{I}_s, + jX_s \hat{I}_s \tag{17} \]

\[ \hat{U}_a = jS X_s \hat{I}_s + s \hat{R}_s \hat{I}_s \tag{18} \]

\[ \hat{U}_s = (R_s + jX_s) \hat{I}_s + jX_s \hat{I}_s \tag{19} \]

\[ \hat{U}_s = j(2-s) X_s \hat{I}_s + \left( R_s + j(2-s) X_s \right) \hat{I}_s. \tag{20} \]

where \( s = \frac{\omega}{\omega_m} \)

From Eqs. (17-20), the steady state equivalent circuits of positive and negative sequence components of DFIG are illustrated in Figs. 2a and 2b, respectively.

Therefore, the positive and negative torque equations are:

\[ T_s = \frac{2}{3} \frac{P}{\omega} \frac{X_s}{\omega} \text{Im} \left[ \hat{I}_s, \hat{I}_s \right] \tag{21} \]

\[ T_r = \frac{2}{3} \frac{P}{\omega} \frac{X_s}{\omega} \text{Im} \left[ \hat{I}_r, \hat{I}_r \right] \tag{22} \]

The total torque is the summation of both positive and negative torque. Clearly, the negative torque and also pulsating torque can be minimized if the negative sequence component of both stator and rotor current are zero.

From Eqs. (19) and (20), the negative stator and rotor currents can be determined by:

\[ \hat{i}_s = \frac{1}{D} \left( \frac{R_s}{2-s} + jX_s \right) \hat{U}_s, - \frac{jX_s}{2-s} \hat{U}_s \tag{23} \]

\[ \hat{i}_s = \frac{1}{D} \left( R_s + jX_s \right) \hat{U}_s, - \frac{jX_s}{2-s} \hat{U}_s \tag{24} \]

where \( D = \left( R_s + jX_s \right) \frac{R_s}{2-s} + \frac{jX_s}{2-s} \)

In Eq. (23), the negative rotor voltage that eliminates the negative stator current can be calculated as in Eq. (25):

\[ \hat{U}_s = \frac{X_s}{X_m} (2-s) \hat{U}_s, - \frac{jX_s}{X_m} \hat{U}_s. \tag{25} \]

Likewise, the negative rotor voltage to eliminate negative rotor current in Eq. (24) is:

\[ \hat{U}_r^* = \frac{X_s}{X_m} (2-s) \hat{U}_r, + \frac{jX_s}{X_m} \hat{U}_r. \tag{26} \]

\[ R_s \text{ and } R_R \text{ which are normally small and the imaginary part in Eqs. (25) and (26) can be neglected. Furthermore, } X_R, X_S \text{ and } X_m \text{ are nearly equal. As a result, the negative rotor voltage can be approximated to:} \]

\[ \hat{U}_r^* = (2-s) \hat{U}_r. \tag{27} \]

The time varying negative sequence component of compensate rotor voltage can follow the relationship in Eq. (27).

\[ \hat{u}_r^* = (2-s) \hat{u}_r. \tag{28} \]

Therefore, if the rotor voltage is fed with the negative sequence component given in Eq. (28), the negative sequence stator and rotor currents and pulsating torque can be reduced.

The 3-phase negative sequence rotor voltages are determined from the instantaneous negative sequence component of stator voltage and added to the rotor voltage command from a conventional controller as illustrated in Fig. 3. The detail derivation of instantaneous symmetrical components is given in Appendix.
5. Verification of the Proposed Method with Steady State Model

In steady state, the typical torque-slip characteristic of a doubly fed induction machine under unbalanced voltage with a VUF of 100% is illustrated in Fig. 4, without negative sequence rotor voltage compensation. The solid line in the figure represents the positive torque curve, the dotted line is the negative torque curve, and the dashed line is a total torque curve. In Fig. 4, the net torque is increased in generator mode while in motor mode the net torque is reduced. The resulting torque, when the system is compensated with the negative sequence rotor voltage calculated from Eq. (27), is illustrated in Fig. 5. Obviously, the negative torque is minimized nearly equal to zero in the whole range of operation. The average torque is close to the positive torque as in normal operation.

6. Verification of the Proposed Method with Dynamic Model

The performance of the DFIG under unbalanced stator voltage conditions is investigated by computer simulation. The test conditions were set as follows:

- The DFIG was started with balanced voltage until the steady state was reached at time $t = 15$ s.
- At time $t = 15$ s, the supply voltage was changed to unbalanced voltage with VUF = 10%.
At time $t = 18$ s, the compensated negative sequence rotor voltage according to Eq. (28) was added to the rotor voltage command.

After the introduction of unbalanced voltage at $t = 15$ s, the pulsating electromagnetic torque with the frequency of $2\omega$ occurred in DFIG as shown in Fig. 6. The torque oscillation occurred from $t = 15$ s to $t = 18$ s with constant amplitude. The introduction of compensated negative sequence rotor current at time $t = 18$ s, reduced the amplitude of pulsating torque, significantly from 0.26 p.u.peak to peak to 0.02 p.u.peak to peak. The stator reactive power is shown in Fig. 7, which indicates that the reactive pulsation is reduced from 0.35 p.u. peak to peak to 0.026 p.u. peak to peak. Moreover, the unbalanced of 3-phase stator current is also decreased as can be seen in terms of the RMS current response in Fig. 8. Before $t = 15$ s, all 3-phase currents were equal at 0.255 p.u., with unbalanced voltage, the RMS currents changed to $i_a = 0.322$ p.u., $i_b = 0.244$ p.u. and $i_c = 0.265$ p.u. which correspond to the unbalanced current CUF = 8.412%. After compensation with negative sequence rotor voltage at $t = 18$ s, the RMS currents changed to $i_a = 0.255$ p.u., $i_b = 0.300$ p.u. and $i_c = 0.290$ p.u. which correspond to CUF = 4.843%.

The magnitudes of the pulsating torque and the pulsating stator reactive power with (negative sequence voltage) compensation and without compensation for 0 to 20% of voltage unbalanced factors are shown in Figs. 9 and 10, respectively. It can be seen that the magnitudes of pulsating torque and pulsating stator reactive power of the system with compensation are approximately 10 times less than the system without compensation. The magnitudes of the pulsating torque and the pulsating stator reactive power with (negative sequence voltage) compensation and without compensation for 0 to 20% of voltage unbalanced factors are shown in Figs. 9 and 10, respectively. It can be seen that the magnitudes of pulsating torque and pulsating stator reactive power of the system with compensation are approximately 10 times less than the system without compensation.
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Fig. 10 Magnitude of pulsating stator reactive power as function of voltage unbalanced factor (a) with (negative sequence voltage) compensation and (b) without compensation.

current unbalanced factors of the system with compensation are approximately 50% of the system without compensation for the same percentage of the unbalanced voltage factor, as shown in Fig. 11.

When the voltages of two phases are dropped, the result is shown in Fig. 12. Apparently, the pulsating torque and pulsating reactive power of DFIG are reduced by a factor of about 10 when compared with the system without compensation.

7. Conclusions

The study of effect of unbalanced grid voltages on the DFIG is presented in this paper. Electromagnetic torque and reactive power pulsation caused by unbalanced voltages introduce several negative effects on the DFIG. These pulsating torques are the results of the interaction between positive and negative sequence components of the stator and rotor currents. In order to reduce the pulsating torques and reactive powers the compensation of negative sequence rotor voltage was proposed. The negative sequence rotor voltage was derived from the negative sequence of the stator voltage and rotor speed. The compensating voltage was directly added to the rotor voltage command to reduce the negative sequence component of the stator and rotor currents. Verification by computer simulation on the case study confirmed that the proposed method can significantly reduce torque and reactive power pulsations, thus improve the overall operational performance of the DFIG with unbalanced stator voltages.

Acknowledgments

The authors would like to gratefully thank the College of Industrial Technology, King Mongkut’s University of Technology North Bangkok for the financial support.

References


Appendix

Instantaneous symmetrical components

The method of symmetrical components was introduced in complex steady state phasors [13]. The set of sequence components is positive, negative and zero and can be determined from:

\[
\begin{bmatrix}
V_{a0} \\
V_{a+} \\
V_{a-}
\end{bmatrix}
= \frac{1}{3}
\begin{bmatrix}
1 & 1 & 1 \\
1 & a & a^2 \\
1 & a^2 & a
\end{bmatrix}
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}
\]  \hspace{1cm} (29)

where \( a = e^{j2\pi/3} \)

For instantaneous symmetrical components, Eq. (29) can be modified by replacing complex phasor with a 120° phase shift operator in time domain as in Eq. (30)

\[
\begin{bmatrix}
V_{a0} \\
V_{a+} \\
V_{a-}
\end{bmatrix}
= \frac{1}{3}
\begin{bmatrix}
V_a + V_b + V_c \\
V_a + S_{120}V_b + S_{240}V_c \\
V_a + S_{240}V_b + S_{120}V_c
\end{bmatrix}
\]  \hspace{1cm} (30)

A different transform method of symmetrical components based on 90° phase shift operator is written as in Eq. (31) [14].

\[
\begin{bmatrix}
V_{a0} \\
V_{a+} \\
V_{a-}
\end{bmatrix}
= \frac{1}{3}
\begin{bmatrix}
V_a + V_b + V_c \\
V_a - \frac{1}{2}(V_b + V_c) + \frac{\sqrt{3}}{2}S_{90}(V_b - V_c) \\
V_a - \frac{1}{2}(V_b + V_c) - \frac{\sqrt{3}}{2}S_{90}(V_b - V_c)
\end{bmatrix}
\]  \hspace{1cm} (31)