Improved Control Technique of Line Side Converter for Doubly fed Induction Generator Wind Turbine System under Unbalanced Voltage Conditions

Suksan Wangsathitwong

***Abstract*— *This paper presents a control method of line side converter for doubly fed induction generator in wind turbine energy system under unbalanced voltage conditions. The unbalanced voltages cause ripple in dc bus and oscillation in instantaneous active and reactive powers. The proposed control technique is to minimize the oscillation components in active and reactive powers by feeding the compensate currents. These compensate currents are determined from the unbalanced voltage information. The outputs of the compensated current controllers are added to the conventional controller. Consequently, the oscillations in dc bus voltage, active and reactive powers are significantly reduced. The simulation results show that the oscillation in dc bus and active power are reduced by over 30% and 70%, respectively.*

***Keywords*— Line side converter, doubly fed induction generator, unbalanced voltage.**

1. INTRODUCTION

Wind power generation is an important alternative renewable energy due to a smaller environmental impact and clean energy supply. The world wind power installation has been growing at the rate of nearly 30% per year for the last 10 years as depict in Fig.1 [1]. Total world wind capacity at the end of 2009 was around 158 GW [2]. The main wind turbine is the variable speed generator due to the maximum power extraction can be controlled. Today, doubly fed induction generators (DFIG) are commonly used by the wind turbine industry for larger wind turbines. Nearly 50% of the market share is DFIG type [3]. The major advantage of these facilities lies in the fact that the power rate of the inverters is around the 25-30% of the nominal generator power. Approximately 2 to 3% efficiency improvement can be obtained due to the small size of power converters. The main basic block diagram of DFIG wind turbine system is illustrated in Fig. 2. The turbine converts the wind energy into mechanical energy. The generator converts mechanical power to electrical power at the stator winding. The generator speed and power are control through two back-to-back variable frequency power converters with a dc link at the rotor terminal.

One converter is connected to the generator and is called machine side converter while another converter is connected to the ac supply and is called line side converter. The main objective of the machine side converter is to control active power or speed of the generator at the maximum power extraction from wind energy and to regulate stator power factor at unity. The line side converter during normal operation is to regulate the dc bus voltage at the reference value and to operate at unity power factor, low harmonic distortion of line currents and operate under grid voltage distortion or unbalanced voltage.

In general, the conventional control method of line side converter is based on synchronously rotating reference frame. After transformation, voltage and current in steady state are dc values and can be easily controlled by PI controller. In this reference frame, the active power and reactive power are decoupled from each other and the powers flow between the grid and the dc link can be independently controlled.

However, wind turbines energy system 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 voltage is due to, for example, unbalanced loads, large single-phase loads and untransposed lines. Severe voltage unbalances can also be caused by unbalanced faults. The unbalanced voltage condition introduces many negative effects to the performance of wind turbine system. Under unbalanced system voltages, the desirable features, such as unity power factor and constant dc bus voltage in the line side converter cannot be assured using conventional control method. If an unbalanced voltage occurs, a ripple at twice the grid frequency appears on the dc bus, as well as on the active and reactive power. However, all the advantages of the PWM line side converter are valid only with the assumption of balanced input system voltage conditions. Nevertheless, the unbalanced voltage conditions occur frequently in the input supply, particularly in a weak ac system.

Generally, a conventional PI control system can reduce unbalanced voltage to some extent but the effects from unbalanced voltage remain significant. Actually, many control algorithms have been proposed for operation of the line side converter under unbalanced input voltage conditions. The purpose of these algorithms is to maintain constant dc bus voltage on the line side. One approach is to use a bulky filter capacitor to remove the ripples in the dc bus voltage; however, it would slow down the dynamic response of the converter, increase the converter size and total cost. Therefore, the efficient

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method is to improve control system in order to minimize the ripple so that small size of capacitor can be achieved and also the dynamic response [4].

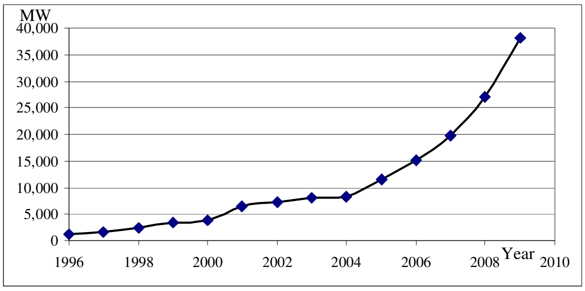


Fig. 1. Global annual install capacity.

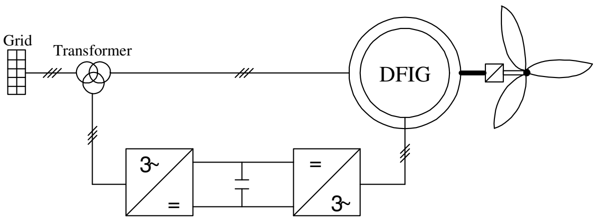


Fig. 2. Block diagram of doubly fed induction generator wind turbine system.

The ripple on the dc bus and on the active power can be eliminated by using a combined positive and negative synchronous reference frame controller [5]. Nevertheless, this controller assures good performance only in steady state. In [6], the switching functions concepts for individual legs of line side voltage source converter are directly computed and switching pulses are generated according to the positive and negative sequence components of system voltage. The input current, *d-q* component of positive and negative sequence currents are calculated from a set of nonlinear equations and fed to the control system as current references are reported in [7]. In [8], the synchronous reference frame of line side converter is coordinated with the machine side converter and current references are calculated from the dc bus voltage, grid ac voltage, active power and reactive power reference. In order to obtain the current references, the complex computation process is employed. Minimizing only the input negative current is presented in [9].

Three single phase line side converters with a common capacitor instead of a three-phase converter was introduced in [10] with the application to the distribution static synchronous compensator (DSTATCOM). The application of three single phase converters to the line side converter is reported in [11]. The problem of ac voltage unbalance can then be avoided, and the voltage fluctuation of dc link can be reduced by more than 50%. With this configuration, each converter can be independently controlled; thus the converter reliability is improved. Moreover, the control method to reduce the oscillation component in instantaneous active power is presented in [12]. Due to the dc bus voltage is related to the active power. Then the ripple voltage will be reduced.

In this paper, a control of ripple voltage in dc bus is presented. The technique is to control the oscillation components in both instantaneous active and reactive power. The reference ac components of *d-q* axis current are calculated and controlled in order to minimize the oscillation terms in active and reactive power. Therefore, the ripple voltage in dc bus will be reduced.

This paper is organized as follows. In Section 2, the modeling of three-phase line side converter is presented. In Section 3, the proposed control method is described. Simulation results are provided in Section 4 and the conclusion is given in Section 5.

2. MODELING AND CONTROL OF LINE SIDE CONVERTER

The schematic diagram of a line side converter is shown in Fig. 3. The circuit in Fig. 3 is analyzed under the following assumptions:

1) The input voltages are balanced.

2) The input impedances are balanced.

3) The converter is lossless.

The three-phase voltage equation of the converter is presented in the following equation.

$$\begin{bmatrix} u_{sysa} \\ u_{sysb} \\ u_{sysc} \end{bmatrix} = R\begin{bmatrix} i_{sysa} \\ i_{sysb} \\ i_{sysc} \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_{sysaa} \\ i_{sysb} \\ i_{sysc} \end{bmatrix} + \begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \end{bmatrix} \quad (1)$$

The dc bus power equation is

$$Ei_{msc} + EC\frac{dE}{dt} = Ei_{dc} = P_{dc} \quad (2)$$

In Park's *d-q* frame that synchronously rotates with the line voltage angular speed ω, the voltage equations in (1) can be represented by

$$u_{sysd} = Ri_{sysd} + L\frac{di_{sysd}}{dt} - \omega Li_{sysq} + u_{sd} \quad (3)$$

$$u_{sysq} = 0 = Ri_{sysq} + L\frac{di_{sysq}}{dt} + \omega Li_{sysd} + u_{sq} \quad (4)$$

The instantaneous active and reactive power components can be represented in terms of the *d-q* axis components of system voltage and currents as follows.

$$\begin{aligned} s &= \frac{2}{3}\vec{u}_{sysdq}\vec{i}^{\,*}_{sysdq} \\ &= p + jq \end{aligned} \quad (5)$$

$$\begin{bmatrix} p \\ q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} u_{sysd} & u_{sysq} \\ u_{sysq} & -u_{sysd} \end{bmatrix} \cdot \begin{bmatrix} i_{sysd} \\ i_{sysq} \end{bmatrix} \quad (6)$$

$$p = \frac{2}{3}\left(u_{sysd}i_{sysd} + u_{sysq}i_{sysq}\right) \quad (7)$$

$$q = \frac{2}{3}\left(u_{sysq}i_{sysd} - u_{sysd}i_{sysq}\right) \quad (8)$$

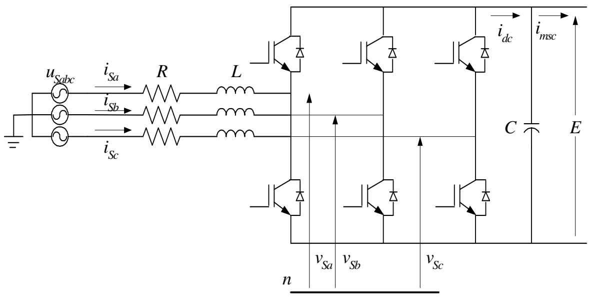


Fig. 3. Line side converter model.

When the converter is lossless, then the instantaneous dc power in (2) and ac power in (7) are equal. Then the dc bus voltage and active power are related.

In (7) and (8), when *d*-axis component is aligned on the phase voltage and u_{sysq} is equal zero. Therefore, the dc bus voltage can be controlled by the *d*-axis current components (i_{sysd}) while the reactive power is controlled by *q*-axis current (i_{sysq}). Consequently, the dc bus voltage or active power and reactive power are decouple controlled and the block diagram of the line side converter control can be designed and depicted in Fig. 4.

The control objective in Fig. 4 is to control the dc bus voltage and *q*-axis current (i_{sysq}) or reactive power at a reference value. Some important characteristics of the control loop in Fig. 4 are noted here:

1. The grid voltages are measured and used to derive the angle of the system voltage (ωt).
2. The dc bus voltage, *q* and *d* components of system current are used as feedback signals for dc bus voltage and currents control. Moreover, the system currents are also used as feedforward signals for deriving the decoupling terms
3. In the dc bus voltage control loop, the dc voltage is measured and fed back for comparison. A PI controller is used to regulate the dc bus voltage. The *d* component of system current, from the controller is the input of another PI controller. The feedforward signal is added to the output of the current controller to decouple the *q*-component from the voltage equation.
4. Similar reasoning can be used to describe the signal flow in the *q* component of the system current loop.

3. CONTROL METHOD UNDER UNBALANCED VOLTAGE

When the grid voltage is unbalanced, the *d-q* axis voltage and current components are oscillated or composed of dc and ac terms. These components can be extracted to two terms as in (9) and (10).

$$\begin{aligned} u_{sysdq} &= u_{sysd} + ju_{sysq} \\ &= \left(\bar{u}_{sysd} + \tilde{u}_{sysd}\right) + j\left(\bar{u}_{sysq} + \tilde{u}_{sysq}\right) \end{aligned} \tag{9}$$

$$\begin{aligned} i_{sysdq} &= i_{sysd} + ji_{sysq} \\ &= \left(\bar{i}_{sysd} + \tilde{i}_{sysd}\right) + j\left(\bar{i}_{sysq} + \tilde{i}_{sysq}\right) \end{aligned} \tag{10}$$

Accordingly, the instantaneous active and reactive power in (6) can be described as.

$$\begin{aligned} \begin{bmatrix} p \\ q \end{bmatrix} &= \frac{2}{3}\begin{bmatrix} \bar{u}_{sysd} + \tilde{u}_{sysd} & \bar{u}_{sysq} + \tilde{u}_{sysq} \\ \bar{u}_{sysq} + \tilde{u}_{sysq} & -\bar{u}_{sysd} - \tilde{u}_{sysd} \end{bmatrix} \cdot \begin{bmatrix} \bar{i}_{sysd} + \tilde{i}_{sysd} \\ \bar{i}_{sysq} + \tilde{i}_{sysq} \end{bmatrix} \\ &= \left(\bar{p} + \tilde{p}\right) + j\left(\bar{q} + \tilde{q}\right) \end{aligned} \tag{11}$$

when the dc components of active and reactive power are

$$\begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \bar{u}_{sysd} & \bar{u}_{sysq} \\ \bar{u}_{sysq} & -\bar{u}_{sysd} \end{bmatrix} \cdot \begin{bmatrix} \bar{i}_{sysd} \\ \bar{i}_{sysq} \end{bmatrix} \tag{12}$$

The ac components of active and reactive power are

$$\begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} u_{sysd} & u_{sysq} \\ u_{sysq} & -u_{sysd} \end{bmatrix} \cdot \begin{bmatrix} \tilde{i}_{sysd} \\ \tilde{i}_{sysq} \end{bmatrix} + \frac{2}{3}\begin{bmatrix} \tilde{u}_{sysd} & \tilde{u}_{sysq} \\ \tilde{u}_{sysq} & -\tilde{u}_{sysd} \end{bmatrix} \cdot \begin{bmatrix} \bar{i}_{sysd} \\ \bar{i}_{sysq} \end{bmatrix} \tag{13}$$

Owing to the active power and dc bus voltage are related as described in (2) and (7). Therefore, the oscillation in dc bus voltage can be reduced if the oscillation in active power in (13) is equal zero.

Consequently, the ac components of active and reactive power in (13) are equal zero when the ac components of *d-q* axis system currents are

$$\begin{aligned} \begin{bmatrix} \tilde{i}_{sysd} \\ \tilde{i}_{sysq} \end{bmatrix} &= -\begin{bmatrix} u_{sysd} & u_{sysq} \\ u_{sysq} & -u_{sysd} \end{bmatrix}^{-1} \begin{bmatrix} \tilde{u}_{sysd} & \tilde{u}_{sysq} \\ \tilde{u}_{sysq} & -\tilde{u}_{sysd} \end{bmatrix} \begin{bmatrix} \bar{i}_{sysd} \\ \bar{i}_{sysq} \end{bmatrix} \\ &= -\frac{1}{u_{sysd}^2 + u_{sysq}^2}\begin{bmatrix} u_{sysd} & u_{sysq} \\ u_{sysq} & -u_{sysd} \end{bmatrix} \begin{bmatrix} \tilde{u}_{sysd} & \tilde{u}_{sysq} \\ \tilde{u}_{sysq} & -\tilde{u}_{sysd} \end{bmatrix} \begin{bmatrix} \bar{i}_{sysd} \\ \bar{i}_{sysq} \end{bmatrix} \end{aligned} \tag{14}$$

As a result, the compensate *d-q* axis ac current components are as follows.

$$\begin{aligned} \tilde{i}_{sysd}^{*} = -\frac{1}{u_{sysd}^2 + u_{sysq}^2}&\left[u_{sysd}\left(\tilde{u}_{sysd}\bar{i}_{sysd} + \tilde{u}_{sysq}\bar{i}_{sysq}\right)\right. \\ &\left. + u_{sysq}\left(\tilde{u}_{sysq}\bar{i}_{sysd} - \tilde{u}_{sysd}\bar{i}_{sysq}\right)\right] \end{aligned} \tag{15}$$

$$\begin{aligned} \tilde{i}_{sysq}^{*} = -\frac{1}{u_{sysd}^2 + u_{sysq}^2}&\left[u_{sysq}\left(\tilde{u}_{sysd}\bar{i}_{sysd} + \tilde{u}_{sysq}\bar{i}_{sysq}\right)\right. \\ &\left. - u_{sysd}\left(\tilde{u}_{sysq}\bar{i}_{sysd} - \tilde{u}_{sysd}\bar{i}_{sysq}\right)\right] \end{aligned} \tag{16}$$

According to (15) and (16), the compensated ac current components controller can be determined and added to the conventional control system as illustrated in Fig. 5. The summation of ac voltage components reference ($\tilde{u}_{sdq}^{*}$) and the reference voltage from Fig. 4 ($\bar{u}_{sdq}^{*}$) are the reference of line side converter terminal voltage (u_{sdq}^{*}). When the line side converter terminal voltage is controlled as shown in Fig. 5, the oscillation components in active and reactive power will be minimized. Subsequently the ripple voltage in dc bus is also reduced.

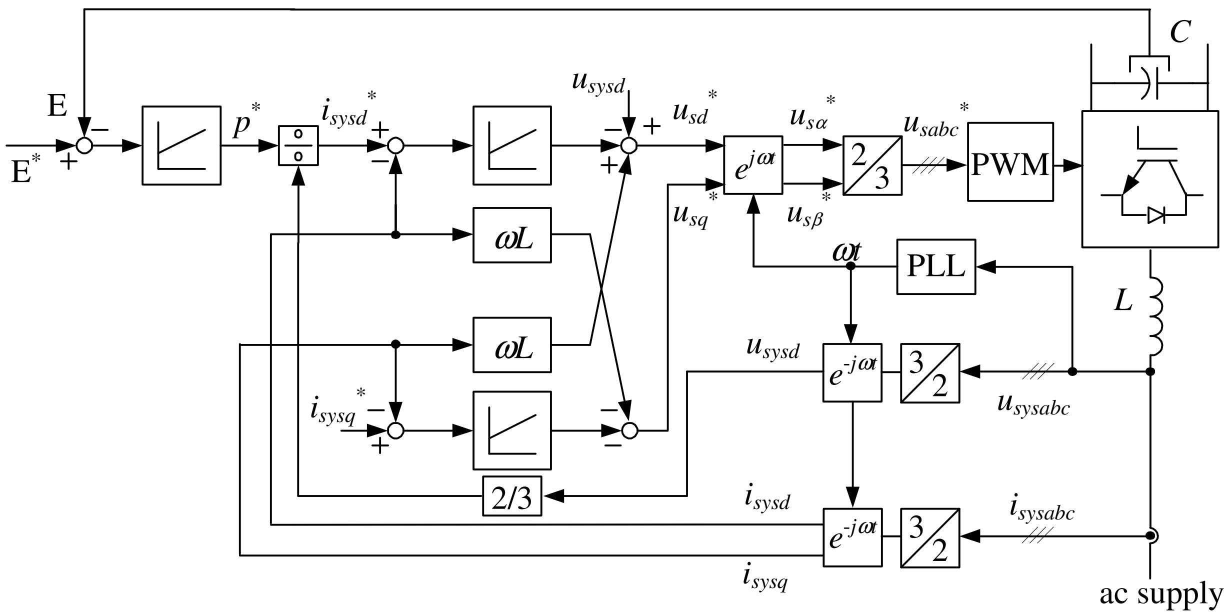


Fig. 4. Control structure of line side converter.

The extraction of the dc and ac components of system voltages and currents can be achieved as depicted in Fig. 6. The dc components can be detected using a low pass filter and ac components are the difference between the *d–q* axis components and the dc components.

4. CASE STUDY

The proposed control method has been verified by computer simulation with single phase and two-phase voltage drop. The simulation parameters are shown in the appendix B. The results are as follows.

Case 1: Single phase voltage drop

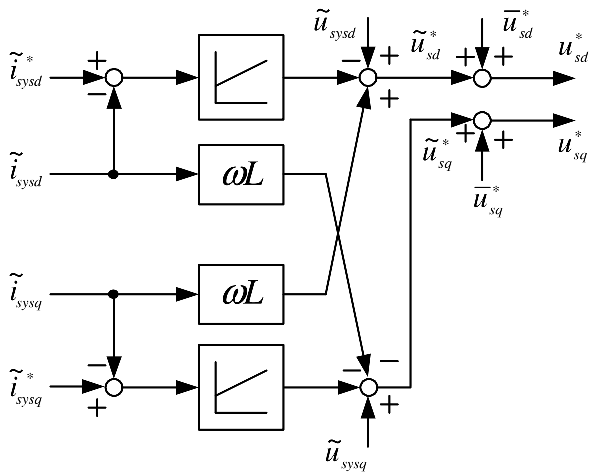


Fig. 5. Control diagram of ac compensate current

The results of the proposed method are shown in Fig. 7. The simulation was started at t = 0 s with balanced system voltage until t = 0.5 s. During this period, the instantaneous dc bus voltage, active and reactive powers were constant at the reference values. At t = 0.5 s, the phase *a* voltage was dropped 40% or VUF = 15.4% immediately as in Fig. 7a. At this time, the control method as in Fig.4 was operated without the compensation of ac current components. Obviously, there were oscillations in dc bus voltage and instantaneous power. After t = 0.8 s, the ac compensate currents in (15) and (16) were controlled and added to the output of the conventional line side converter control system as in Fig. 5. Apparently, the oscillations of dc bus voltage, active power and reactive power were significantly reduced. It can be seen that the proposed control method can reduce the oscillation in active power by 75%, while the ripple in reactive power was reduced by 45% and the ripple in the dc bus voltage by 40%. According to (15) and (16), the *d-q* axis current was increased as shows in Fig. 7d. Whereas Fig. 7e shows the compensate ac currents waveforms. After t = 0.8 s, these currents were fed to the control system and the ripples were immediately decreased.

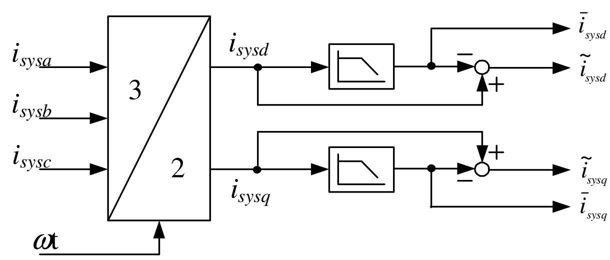
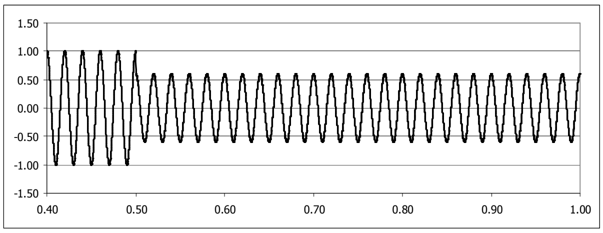


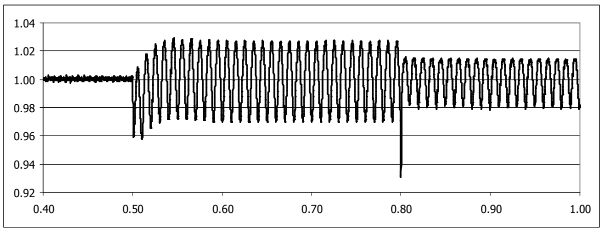
Fig. 6. Block diagram for dc and ac components separation.

Case 2: Two-phase voltage drop

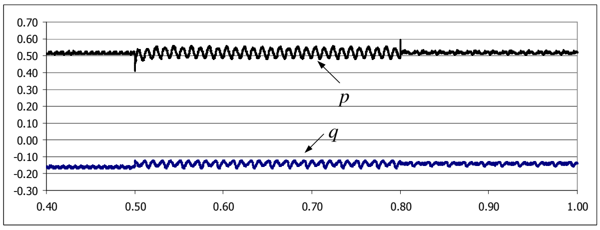
The condition in case of the two-phase voltage drop was same as in single phase voltage drop. At t = 0.5 s, the phase *b* and *c* voltages were dropped 40% or VUF = 18.2% and the control system was worked without compensate ac currents. After t = 0.8 s, the ac compensate currents in (15) and (16) were controlled and fed to the converter. The simulations results are illustrated in Fig. 8a to Fig.8d. The results show that the proposed control method can reduce the oscillation in active power and reactive power by 86% and 75%, respectively while the ripple in dc bus was decreased 30%.



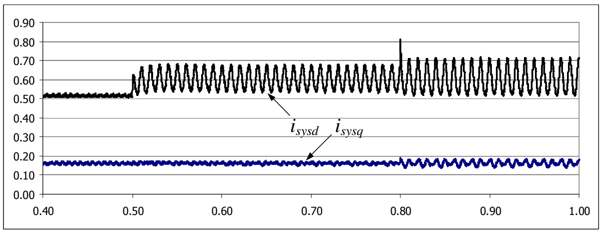
a). Phase *a* system voltage



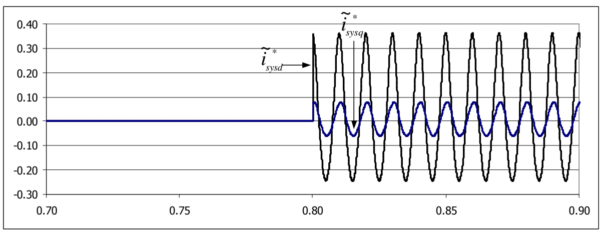
b). DC bus voltage



c). Instantaneous active and reactive power

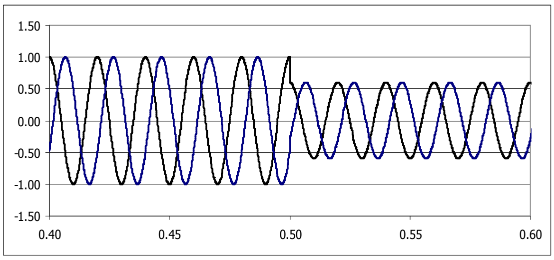


d). Direct and quadrature axis system currents

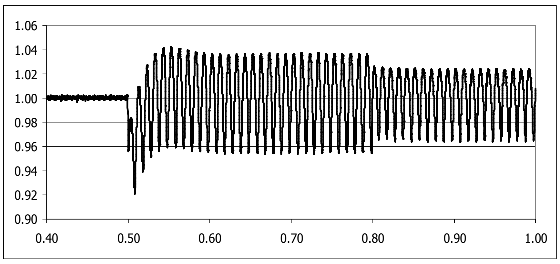


e). Compensate ac *d-q* axis currents

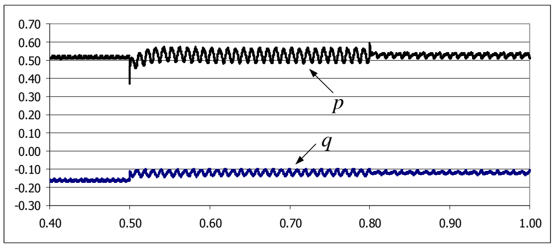
Fig. 7. System response in one phase voltage drop.



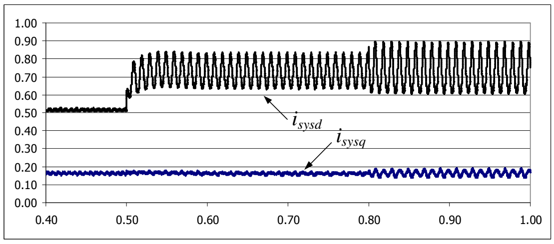
a). Phase *a* and *b* system voltage



b). DC *bus* voltage



c). Instantaneous *active* and reactive power



d). Direct and *quadrature* axis system currents

Fig. 8. System response in two-phase voltage drop

Table 1. Comparative study with other technique

Reduction of Oscillation (%)	Proposed method	Other method
Single phase drop :		
Active power	75	70
dc bus voltage	45	40
Two-phase drop :		
Active power	86	80
dc bus voltage	30	30

Fig. 9 shows the phase b system current. When the grid voltages were balanced, the current waveform was sinusoidal. At t = 0.5 s, the current was distorted and increased due to unbalanced voltage. Apparently, the increase of system current after t = 0.8 s owing to the operation of compensated current controller in Fig. 5.

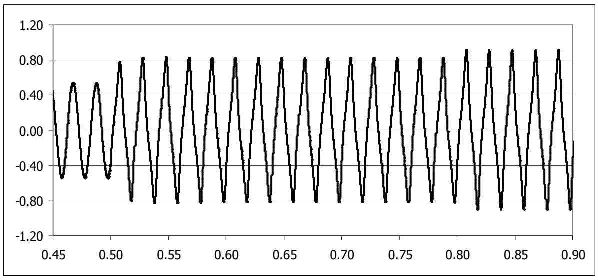


Fig. 9. Phase b system current

The simulation results have been compared to method in [12] as depicted in Table 1.

Table 1. Comparative study with other technique

Reduction of Oscillation (%)	Proposed method	Other method
Single phase drop :		
Active power	75	70
dc bus voltage	45	40
Two-phase drop :		
Active power	86	80
dc bus voltage	30	30

The results show that the proposed control method can reduce the oscillations of active power and dc bus voltage more than the [12] about 5%.

5. CONCLUSIONS

A control technique to minimize ripple in dc bus voltage, active power and reactive power for line side converter in DFIG wind energy system is proposed. The compensate ac components in *d-q* axis current is calculated, from the unbalanced information of three-phase grid voltage, and controlled in combination with the conventional line side converter control system. The compensate currents are used to reduced the oscillation in instantaneous active power, reactive power and dc bus voltage. The simulation results show that, with the proposed technique, the ripple in dc bus and active power were significantly decreased by over 30% and 75%, respectively.

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NOMENCLATURE

C DC bus capacitor

E DC bus voltage

i_{Sabc} 3-phase system current

i_{dc} DC bus current

i_{msc} Machine side dc current

$\bar{i}_{sysd,q}$ DC component of *d-q* axis current

$\tilde{i}_{sysd,q}$ AC component of *d-q* axis current

$\vec{i}_{sysd,q}$ *D-Q* axis current vector

L Filter inductance

p instantaneous active power

P_{dc} DC bus power

q Instantaneous reactive power

R Filter resistance

u_{sabc} Three-phase line side converter terminal voltage

u_{sysabc} Three-phase system voltage

$\bar{u}_{sysd,q}$ DC component of *d-q* axis voltage

$\tilde{u}_{sysd,q}$ AC component of *d-q* axis current

$\vec{u}_{sysdq}$ *D-Q* axis voltage vector

ω System voltage angular speed

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APPENDIX A

Three-phase voltage or current is balanced or symmetrical if all the three phases have the same amplitude and a phase shift of 120^0 respect to each other. If either or both of these conditions are not met, the system is called unbalanced or asymmetrical.

There are two general definitions for measuring the voltage unbalanced, NEMA and IEC. Based on the IEC standard [13], the unbalanced voltage is defined by the voltage unbalanced factor given by

$$\text{Voltage unbalanced factor, VUF (\%)} = \frac{V_2}{V_1} \times 100 \qquad \text{(A-1)}$$

where V_1 and V_2 are positive and negative sequence components of voltage, respectively.

APPENDIX B

The parameters of the studied system are given as follows

- nominal line voltage = 380 V at 50 Hz;
- filter inductor = 5 mH;
- dc-link capacitor = 220 □F;
- dc-link voltage = 600 V;
- switching frequency = 10 kHz