A Novel Control Scheme for DFIG-based Wind Energy Systems under Unbalanced Grid Conditions

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Abstract

This paper presents an analysis and a novel control scheme for a doubly-fed induction generator (DFIG) based wind energy generation under unbalanced grid conditions. The control objectives are: (i) to limit the rotor currents, (ii) to suppress ripples in the torque and (iii) to suppress the dc-link voltage fluctuation through converter controls. Negative sequence compensation techniques by one of the converters in a DFIG are discussed and their limitations are presented. A coordinated control scheme with a concise structure is proposed in this paper. The rotor side converter (RSC) is controlled to suppress ripples in the torque and the rotor currents while the grid side converter (GSC) is controlled to suppress ripples in the dc-link voltage by considering the rotor power effect. The major contributions of the paper include: (i) presentation of the limitation of negative sequence compensation using one converter; (ii) development of a much simpler control scheme compared with the widely used dual sequence control scheme. In the proposed control scheme, low pass filters are not necessary and only one reference frame for each converter is used. Matlab/Simulink tests for a 2MW DFIG demonstrate the effectiveness of the control scheme.

Keywords: DFIG, Unbalance, RSC, GSC, DC-link Voltage, Torque Ripple

Nomenclature

ω_s, ω_r, ω_m	Stator, rotor and rotating angular frequency.
$\overline{I}_s$, $\overline{I}_r$	Stator, rotor current vectors. $\overline{I} = \frac{1}{\sqrt{2}}(i_q - ji_d)$.
$\overline{V}_s$, $\overline{V}_r$	Stator, rotor voltage vectors. $\overline{V} = \frac{1}{\sqrt{2}}(v_q - jv_d)$.
$\overline{I}_g$, $\overline{V}_g$	Grid side converter current, voltage vectors.
i_{qs}, i_{ds}	q-axis and d-axis stator currents.
i_{qr}, i_{dr}	q-axis and d-axis rotor currents referring to the stator side.
Subscripts	
s, r, g	Stator, rotor and grid.
$+, -$	Positive, negative components.
q, d	Rotating reference frame q axis and d axis.
Superscripts	
$+, -$	Synchronous, negative synchronous reference frames.

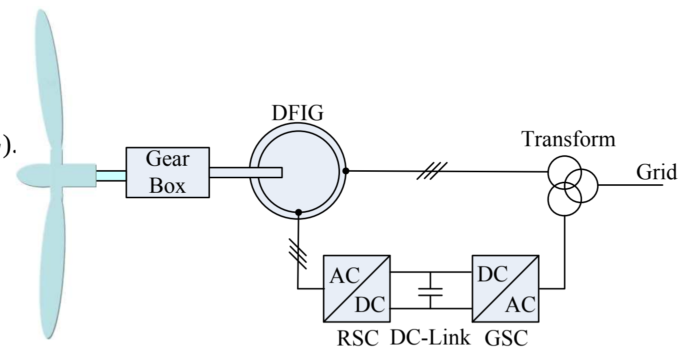

Figure 1: Schematic diagram of a DFIG-based wind generation system.

1. Introduction

Doubly-fed induction generator (DFIG)-based wind generation (Fig. 1) is the state-of-the-art wind generator technology. The stator of a DFIG is connected directly to the grid while the rotor of a DFIG is connected through the rotor side converter (RSC), the dc-link and the grid side converter (GSC) to the grid.

Unbalanced stator conditions in DFIGs give rise to high frequency components in rotor currents and torque pulsations which can cause excessive shaft stress and winding losses [1]. Existing control techniques in literature to minimize the torque pulsations include (i) rotor-side converter (RSC) compensation by supplying negative sequence voltages to the rotor circuits [2, 3] to suppress the negative sequence components in the rotor currents and ripples in the electromagnetic torque, or (ii) grid-side converter (GSC) compensation by compensating negative sequence currents to the grid [4] to keep the stator currents free of negative sequence components and thus eliminate the negative sequence components in the rotor currents. In [2–4], negative sequence compensation control schemes are applied through the RSC to eliminate torque pulsations. DC-link voltage ripples are not in the consideration.

Large ripple in the dc-link voltage ripple is another concern under unbalanced grid conditions. To suppress the dc-link voltage ripples and at the same time to suppress the pulsations in the rotor currents and the torque, coordinated control schemes for both the RSC and GSC are proposed in [5–8].

Negative sequence compensation can be realized through current control loops [3–9], or through direct power control [10, 11]. Cascaded control structure with inner fast current control and outer slower power/voltage control is used in the commercial DFIG technology [12] and hence is also used widely in existing research. In cascaded control structure, the coordination scheme is to use the RSC to limit the torque and rotor current fluctuations and to use the GSC to suppress ripples in the dc-link voltage [5–8]. Dual sequence control is widely applied in dealing with issues that arise due to unbalanced grid conditions. In dual sequence control, positive and negative sequence components are firstly separated and then controlled via proportional integral (PI) controllers. The negative sequence loops are the supplementary control loops specifically dealing with unbalanced conditions.

The major disadvantages of dual sequence control include its complicated computation for the reference current values and the usage of low pass filters for sequence component separation. To separate positive and negative sequence variables, two reference frames are used, namely, the synchronous reference frame qd^+ and the negative synchronous reference frame qd^-. After applying qd^+ or qd^- transformation, the positive and negative components will become a dc component and an ac component with a frequency of $2\omega_e$ (ω_e is the nominal line frequency). The dc components are extracted using low pass filters. However, these filters contribute excessive time delays and can deteriorate the control performance.

To reduce the number of reference frames used in control, various techniques have been proposed. Proportional resonant (PR) controllers are used if $\alpha\beta$ reference frame is adopted [9] or proportional integral and resonant (PIR) controllers are used if qd^+ reference frame is adopted [13, 14]. These techniques have been exemplified in RSC controls to reduce the torque ripples or rotor current high frequency negative sequence components.

For the GSC control loops, dual sequence control is also applied in [5, 7, 8]. While the positive sequence control loops are used to regulate the dc-link voltage and the terminal voltage, the negative sequence control loops aim to suppress the dc-link voltage ripple. Extensive measurements and computing are required for the control objective.

The purpose of this paper is to investigate negative sequence compensation techniques by the RSC and/or the GSC and develop an easy to implement control scheme that can suppress ripples in both the torque and the dc-link voltage. In our previous work [15], comparison of negative sequence compensation through either RSC or GSC was made. [15] found that negative sequence compensation through GSC is more effective to suppress the ripples in torque. However, ripples in dc-link voltage are not in consideration. This paper will take into consideration of pulsations in the rotor currents and the torque and the ripples in the dc-link voltage. To obtain a concise control structure, PR controllers will be adopted in the RSC control and the method to use rotor power as feedback signal to limit dc-link voltage fluctuation [16] will be adopted in the GSC control. Using the above two approaches, dual sequence control scheme is avoided and hence long computation time and dc filters can all be avoided.

The rest of the paper is organized as follows. In Section 2, the limitation of compensation using one converter will be identified. A coordinated control of RSC and GSC will be developed in Section 3. Comparison of the proposed scheme and the dual sequence control scheme is also presented in this section. Matlab/Simulink tests for a 2MW DFIG to demonstrate the effectiveness of the control scheme and compare the proposed scheme with the dual sequence scheme are presented in Section 4. Section 5 concludes the paper.

2. Negative sequence compensation techniques and their limitations

The transients in rotor voltages due to stator voltage dip are analyzed in [17]. Under unbalanced grid voltage, the most severe operation problems are the torque ripple due to the negative sequence components in the stator and rotor currents and the dc-link voltage ripple [8]. The steady state components in the rotor currents and electromagnetic torque are analyzed in [18]. In one word, due to unbalanced stator voltage conditions, the negative sequence components in the stator currents induces a high frequency component $(\omega_e + \omega_m)$ or $(2 - s)\omega_e$ in the rotor currents and pulsations at $2\omega_e$ frequency in the electromagnetic torque. In this section, negative sequence compensation techniques via one converter and their limitations are presented.

2.1. Negative sequence compensation via GSC

Negative sequence compensation via GSC is presented in [4]. The philosophy is to let the GSCs compensate the negative sequence currents required in the network during any unbalanced operation. The circuit model is shown in Fig. 2. The GSCs will supply the negative sequence current components to the grid. Hence the stator currents will remain balanced. This method is documented in [4].

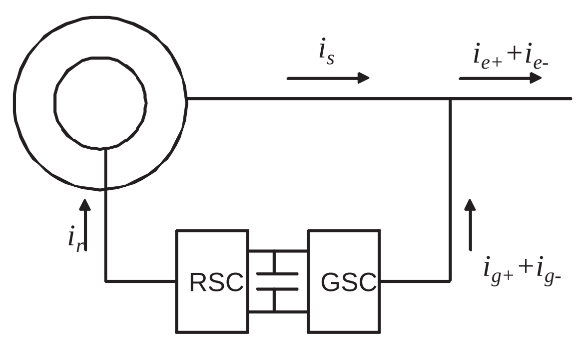

Figure 2: The control philosophy: negative sequence compensation through GSC: $i_{g-} = i_{e-}$. Stator current i_s is free of negative sequence components.

For negative sequence compensation via GSC, the current controllers of the GSC will measure the network currents, extract the negative sequence components and generate the required negative sequence currents for compensation. The reference values of the negative sequence currents come from the measurements of the currents to the grid $i_{e,abc}$. The negative sequence components of $i_{e,abc}$ are then extracted through abc/qd^- transformation and low pass filters.

Since the GSC compensates a negative sequence current to the grid, the three-phase voltage from the GSC should provide the negative sequence component as well. The instantaneous power through the GSC will have pulsating components. The dynamic equation of dc-ink voltage is given by:

$$CV_{dc}\frac{dV_{dc}}{dt} = P_g - P_r \tag{1}$$

where P_g and P_r are the GSC and RSC instantaneous powers. The detailed analysis of the dc-link voltage due to unbalanced grid voltages can be found in [19]. If there is only negative sequence compensation from the GSC, and assume that the rotor power P_r has only dc component, the dc-link voltage will have ripples with two pulsating components at frequencies of $2\omega_e$ and $4\omega_e$ [19]. The more unbalanced the grid voltage, the higher the magnitude of the pulsating power, and hence the higher the magnitude of the dc-link voltage ripple.

2.2. Negative sequence compensation via RSC

Torque pulsation can also be eliminated via negative sequence compensation via the RSC [3, 13]. The steady-state negative sequence circuit model with the RSC compensation can be derived using qd^- reference frame and then relating q-axis and d-axis variables to phasors. The main reason for using qd^- reference frame is that for negative sequence components (currents, voltages), they are "seen" as dc variables at steady-state. And it is easy to relate them to phasors [20]. The circuit model is developed in [18] and is shown in Fig. 3.

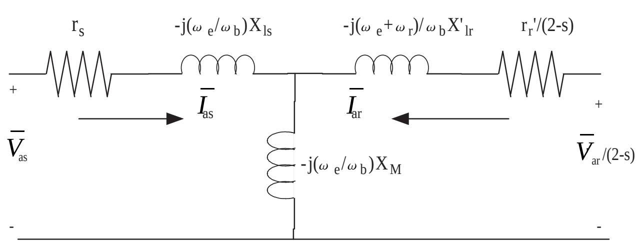

Figure 3: Steady-state negative sequence induction machine circuit representation.

From the circuit model, it can be seen that injecting a negative sequence voltage from the RSC can eliminate the negative sequence rotor current ($\bar{I}_{ar}^- = 0$) or the negative sequence stator current ($\bar{I}_{as}^- = 0$) or the torque pulsation. The derivation of the rotor current reference values to eliminate the torque pulsation can be found in [3].

Without losing the generality, the RSC needs to inject a negative sequence voltage. Similar as the consequence of negative sequence compensation via GSC, the dc-link voltage will have ripples with pulsating components. Therefore using RSC negative sequence compensation alone leads to dc-link voltage ripples.

Analysis in Section 2 presents the limitations of using one converter. Two control objectives, namely torque ripple suppression and dc-link voltage ripple suppression, cannot be achieved simultaneously using either RSC compensation or GSC compensation. Therefore both RSC and GSC controls are used in

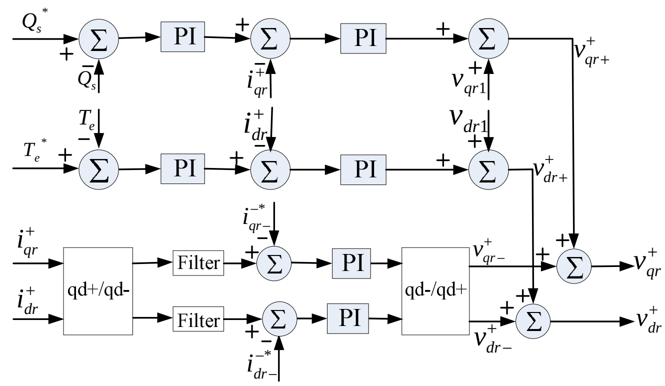

Figure 4: Dual sequence control loops for RSC. $v_{qr1} = s\omega_e\sigma L_r i_{dr} + s\omega_e \frac{L_m}{L_s}\lambda_{ds}$, $v_{dr1} = -s\omega_e\sigma L_r i_{dr}$, where $\sigma = 1 - \frac{L_m^2}{L_s}$.

[5–8]. In Section 3, a concise coordination control structure will be proposed.

3. Proposed Coordination Technique under Unbalanced Grid Condition

Unbalanced grid conditions cause high frequency pulsations in the torque and the rotor currents and ripples in the dc-link voltages. Torque ripples increase the stress of the mechanical components of DFIGs. Constant dc-link voltages are preferred for voltage source converters. Meanwhile the converters have limited capability and the magnitudes of the high frequency rotor current components should be limited. The control objective is three-fold: 1) to suppress torque ripples; 2) to reduce the ripples in the dc-link voltages; 3) to reduce the magnitude of the rotor currents.

The analysis in Section 2 has identified the conflicting nature of negative sequence compensation via RSC or GSC alone. Various control techniques based on RSC-GSC coordination have been proposed in literature. In [5, 6], the RSC is controlled to eliminate the torque oscillations at double supplying frequency while the GSC is controlled to cancel the stator power pulsation. The overall output power from the DFIG system is then kept constant. In [7, 8], the RSC is controlled to eliminate the torque oscillations while the GSC is controlled to keep dc voltage constant by choosing suitable current reference values.

3.1. RSC Control

Dual sequence controllers to separately control the positive sequence and negative sequence rotor current applied in [7, 8] are shown in Fig. 4. Low pass filters are applied to separate the currents after abc/dq transformation. Filters can introduce time delay and deteriorate control performance. Therefore, in [5, 6], the main controller dealing with the positive sequence is implemented without filter, only the auxiliary controller dealing with the negative sequence rotor currents has filters.

The control objective is to eliminate the ripples in the torque and therefore the reference values of the negative sequence rotor currents need to be calculated. The principles of the computation are given in the following paragraphs. The electromagnetic torque can be expressed in the form of the stator flux linkage and the rotor current [20]:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{M}{L_s} real(-j\lambda_s I_r^*). \tag{2}$$

The rotor current space vector and the stator flux linkage space vector in qd^+ reference frame consisting of positive and negative sequence components can be expressed as follows.

$$\begin{cases} I_r^+ = I_{r+}^+ + I_{r-}^- e^{-j2\omega_e t} \\ \lambda_s^+ = \lambda_{s+}^+ + \lambda_{s-}^- e^{-j2\omega_e t}. \end{cases} \tag{3}$$

Therefore, the electromagnetic torque in (2) has three components: $T_e^+ = T_{edc}^+ + T_{ecos}^+ \cos(2\omega_e t) + T_{esin}^+ \sin(2\omega_e t)$,

$$\text{where} \begin{cases} T_{edc}^+ = K(\lambda_{qs+}^+ i_{qr+}^+ + \lambda_{ds+}^+ i_{dr+}^+ + \lambda_{qs-}^- i_{qr-}^- + \lambda_{ds-}^- i_{dr-}^-) \\ T_{ecos}^+ = K(\lambda_{qs+}^+ i_{qr-}^- + \lambda_{ds+}^+ i_{dr-}^- + \lambda_{qs-}^- i_{qr+}^+ + \lambda_{ds-}^- i_{dr+}^+) \\ T_{esin}^+ = K(\lambda_{ds+}^+ i_{qr-}^- - \lambda_{qs+}^+ i_{dr-}^- - \lambda_{ds-}^- i_{qr+}^+ + \lambda_{qs-}^- i_{dr+}^+) \end{cases} \tag{4}$$

where $K = \frac{3}{2}\frac{P}{2}\frac{M}{L_s}$.

To minimize ripples in the electromagnetic torque, the ac components of the torque should be set to zeros, *i.e.*:

$$\begin{cases} T_{ecos}^+ = 0 \\ T_{esin}^+ = 0. \end{cases} \tag{5}$$

From the above requirements, the reference values of the negative sequence rotor currents can be computed based on the reference positive sequence rotor currents and the stator flux linkage measurements. The PI controllers in the negative sequence control loops make sure the negative sequence components in the rotor currents track the referenced values.

Computation of the reference negative sequence currents requires extensive information of the stator flux linkage and the positive sequence reference rotor current. Time delay will be introduced in such control structure and thus a simpler control structure is sought in this paper.

Objectives 1 and 3 have similar consequence since reduction of the negative sequence of rotor current results in reduction of torque ripples. Thus, instead of computing the reference values of the RSC negative sequence currents, the reference values for the negative sequence rotor currents can be set to zeros. This way, pulsations in both the rotor currents and the torque can be suppressed if not fully eliminated. Hence, the purpose of the negative sequence RSC current controller is to eliminate the negative sequence rotor currents and the reference negative sequence rotor currents can be set to zero.

With such knowledge, the dual sequence control structure can be simplified using PR or PIR controller. A PR controller can be considered as an ac signal tracker just as a PI controller is a dc signal tracker [21]. A PR controller has been tested to eliminate the negative sequence rotor current by the authors in

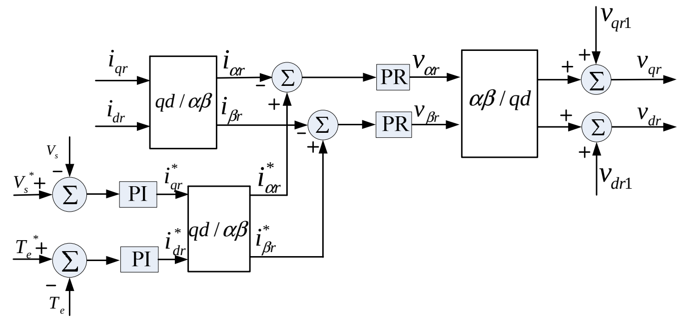

Figure 5: Proposed control loops for RSC. The transfer function in the PR block is $K_P + \frac{K_I s}{s^2+\omega_e^2}$. $v_{qr1} = s\omega_e \sigma L_r i_{dr} + s\omega_e \frac{L_m}{L_s}\lambda_{ds}$, $v_{dr1} = -s\omega_e \sigma L_r i_{dr}$.

[22]. In this paper, the same current control structure is adopted for RSC. The proposed control loops for the RSC is shown in Fig. 5.

Since the negative sequence current reference values are set to zeros, the reference currents in $\alpha\beta$ contain only positive sequence information. The measurements will also be transferred to $\alpha\beta$ frame. Rotor currents in $\alpha\beta$ will only have components with a frequency of ω_e under unbalanced grid voltage conditions. PR controllers are effective for ac signal tracking. Hence the controller will eliminate the negative sequence currents in the rotor circuits.

3.2. GSC Control

The control objective of the GSC control is to keep the dc-link voltage constant. Instead of using dual sequence controller as described in [5–8], a technique in [16] to limit dc-link voltage fluctuation is adopted in the GSC control. The key idea is that the current reference value should change to reflect the instantaneous power transfer through the dc-link. Thus the instantaneous rotor power is measured and used to obtain the current reference value. The method has been verified in [16] for a symmetric voltage dip and it is found that the dc-link voltage fluctuation is effectively limited. In unbalanced grid conditions, the dc-link voltage also suffers fluctuation and the same method will be adopted to limit the fluctuation in this paper

The difference between P_r and P_g causes the ripple in the DC-link voltage. A constant dc-link voltage is preferred in voltage source converters to ensure adequate PWM, while a balanced power transfer between RSC and GSC ensures a constant dc-link voltage. In [5], the GSC current reference values are calculated to ensure the GSC power ripple compensates the RSC power ripple. Thus a constant dc-link voltage can be ensured.

Due to the negative sequence compensation from the RSC, P_r will have ripples and can be expressed as :

$$P_r = P_{rdc} + P_{rcos}\cos(2\omega_e t) + P_{rsin}\sin(2\omega_e t). \tag{6}$$

To keep the dc-link voltage free of ripple, the following requirements are necessary.

$$\begin{cases} P_{rcos} = P_{gcos} \\ P_{rsin} = P_{gsin}. \end{cases} \tag{7}$$

The GSC current reference values can be calculated from (7) given the RSC voltage, grid voltage and RSC current information. The dual sequence GSC control loops used in [5, 7, 8] are shown in Fig. 6. In the above control structure, the calculation of negative sequence grid currents through (7) requires extensive measurements and computation itself is complex. Further, low pass filters introduce time delay and worsen controller performance. A simpler method is sought in this paper.

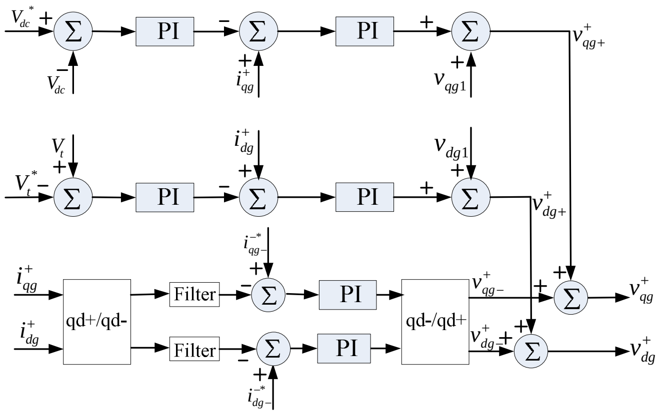

Figure 6: Dual sequence control loops of GSC. $v_{qg1} = v_{qs} + \omega_e L_g i_{dg}$; $v_{dg1} = v_{ds} - \omega_e L_g i_{dg}$. L_g is the inductance of the transformer connecting the GSC to the grid.

When the terminal voltage phasor $\bar{V}_s$ of the DFIG is oriented at q-axis, the qd-axis voltages become: $v_{qs} = V_s$, $v_{ds} = 0$. Hence the GSC power becomes: $P_g = real(V_s I_g^*) = V_{qs} I_{qg}$. Thus, the dc-link voltage dynamic equation can be expressed as:

$$CV_{dc}\frac{dV_{dc}}{dt} = V_{qs} I_{qg} - P_r. \quad (8)$$

Under unbalanced grid conditions, the rotor power P_r has pulsating components. In order to keep the dc-link voltage constant, it is important to consider the rotor power effect. From (8), the desired GSC current can be found as:

$$I_{qg} = \frac{CV_{dc}}{V_{qg}}\frac{dV_{dc}}{dt} + \frac{P_r}{V_{qg}}. \quad (9)$$

Thus, the reference value of I_{qg}^* should have an additional component P_r/V_{qg}^*. The new proposed control of the GSC is shown in Fig. 7.

4. Simulation Studies

Simulation studies with the proposed control are carried out by using Matlab/Simulink for a 2MW DFIG connected to a grid through the network impedance Z. The parameters of the DFIG are given in Appendix. Three scenarios are tested and they are Scenario 1 - with only positive sequence control loops of GSC and RSC, Scenario 2 - with dual sequence control loops of the RSC and GSC as shown in Figs. 4 and 6 and Scenario 3 - with the proposed control of the RSC and GSC as shown in Figs. 5 and 7.

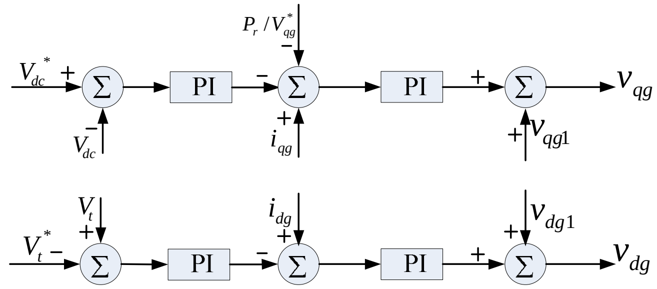

Figure 7: Proposed control scheme for GSC. $v_{qg1} = v_{qs} + \omega_e L_g i_{dg}$; $v_{dg1} = v_{ds} - \omega_e L_g i_{dg}$. L_g is the inductance of the transformer connecting the GSC to the grid.

The Phase A grid voltage will be subjected to a low voltage at 1 second. At 1.5 seconds, the voltage will be recovered, as seen in Fig. 8. The dynamic responses of the electromagnetic torque under the three scenarios are shown in Figs. 9 and 10. It is found that with negative sequence compensation, the ripples in the electromagnetic torque are limited effectively. The simulation results also demonstrate that compared with the dual sequence control, the proposed control scheme is similarly effective.

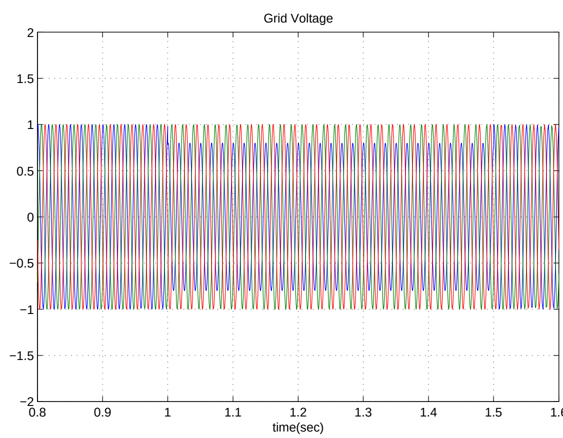

Figure 8: Grid voltage during the study period.

Simulation results of the total power outputs from the DFIG under the three scenarios are shown in Fig. 11 and Fig. 12. Negative sequence compensation techniques can effectively suppress the oscillation of P_e.

The pulsation in the dc-link voltage is caused by the pulsation difference between rotor power and grid power. With dual sequence control (Scenario 2), the pulsation of the dc-link voltage is greatly reduced compared with that in Scenario 1 where only positive sequence control loops are present.

With the new proposed control technique, the negative sequence rotor current components can be effectively suppressed. Consequently, the ripples in T_e and P_r are significantly reduced. Meanwhile, the rotor power P_r is measured and the current reference value is modified accordingly in the dc-link voltage control loop in the GSC. The simulation results of the dc-link volt-

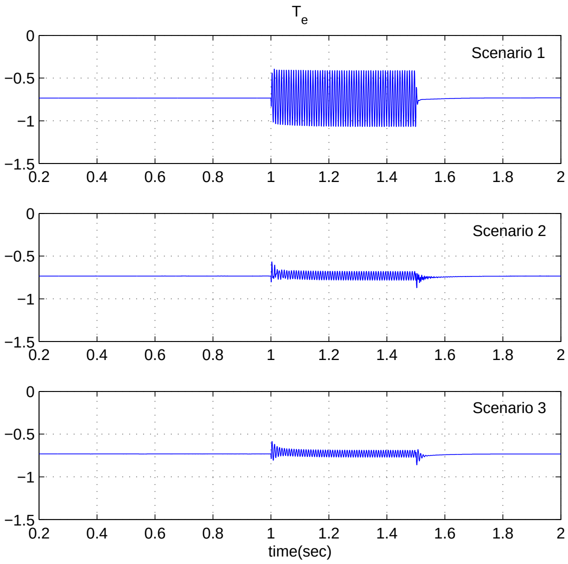

Figure 9: Dynamic responses of electromagnetic torque.

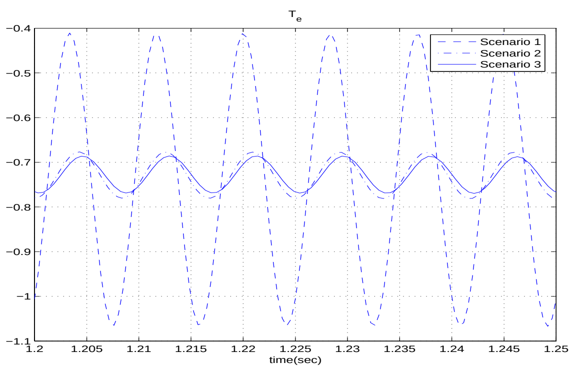

Figure 10: Dynamic responses of electromagnetic torque in the center of grid unbalance.

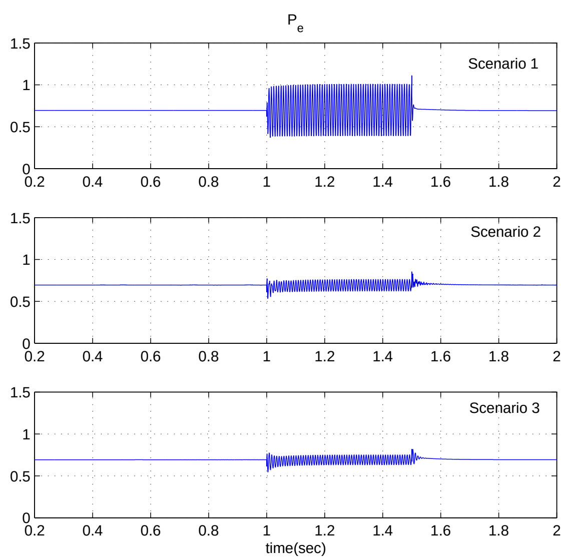

Figure 11: Comparison of the total active power from the DFIG.

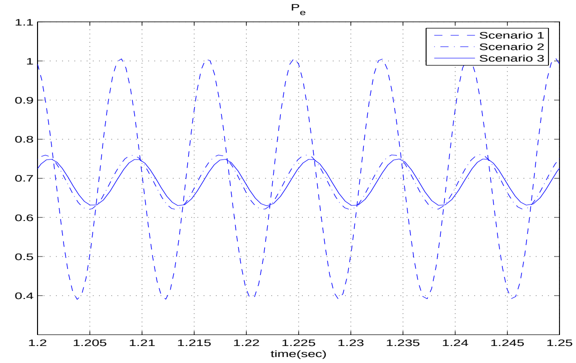

Figure 12: Comparison of the total active power under three scenarios in the center of grid unbalance.

age are shown in Fig. 13 and Fig. 14. It is found that the dc-link voltage ripples are well suppressed.

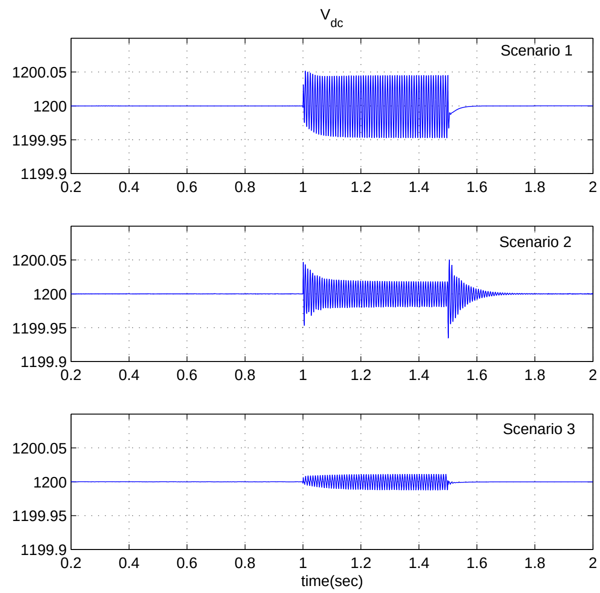

Figure 13: Responses of dc-link voltage under three scenarios.

The dynamic responses of the stator currents are shown in Fig. 15 and the dynamic responses of the rotor currents are shown in Fig. 16. The currents in both *abc* frame and the synchronous reference frame are shown in these plots. It is found that with the proposed control scheme, the negative sequence components in the currents are greatly reduced. These negative sequence components are shown as the high frequency ac components in the synchronous reference frame. In turn, the currents seen in *abc* frame are more balanced.

The dynamic responses of the RSC voltages and the GSC voltages are shown in Figs. 17 and 18. It is found that the RSC voltages are more unbalanced due to the proposed control. This is due to the increased negative sequence compensation from the RSC as shown in Fig. 17. Overall the simulation results show that the proposed control scheme can effectively reduce

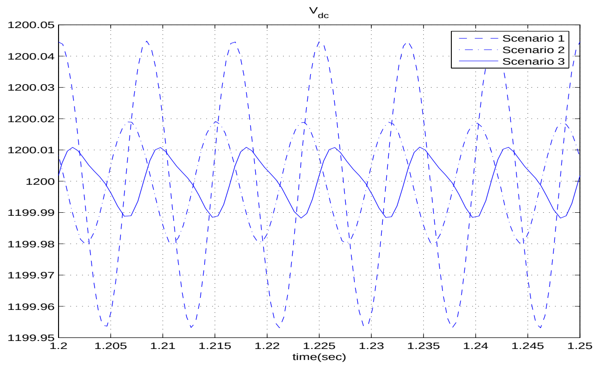

Figure 14: Responses of dc-link voltage in the center of grid unbalance under three scenarios.

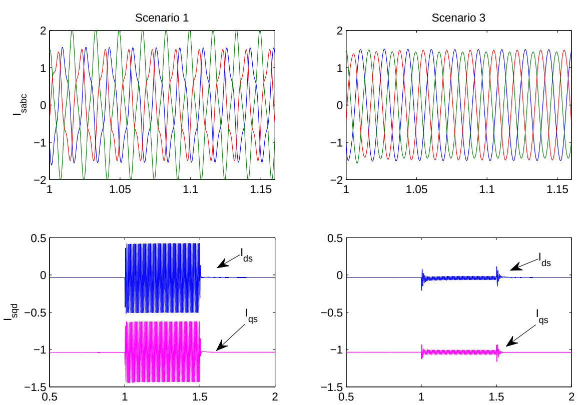

Figure 15: Dynamic responses of stator currents.

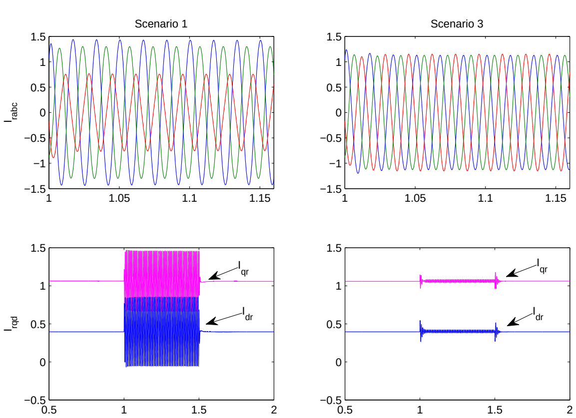

Figure 16: Dynamic responses of rotor currents.

ripples in the torque and in the dc-link voltage. Compared with the existing dual-sequence control scheme, the proposed control has a comparable performance while its control structure is much more concise.

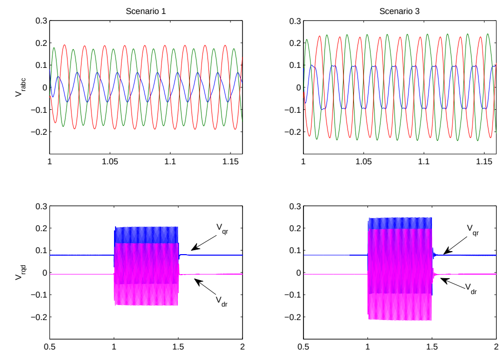

Figure 17: Dynamic responses of rotor voltages.

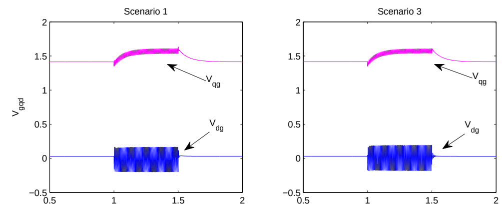

Figure 18: Dynamic responses of GSC voltages.

5. Conclusion

This paper presents an analysis and a control scheme to suppress the pulsations in the rotor currents and the torque and the ripples in the dc-link voltage for a DFIG-based wind energy system under unbalanced grid conditions. The major contributions of the paper include: (i) the presentation of the limitation of negative sequence compensation through one of the DFIG converters; (ii) the proposed coordination control scheme with a concise structure. In the proposed control scheme, the RSC is controlled to suppress the ripples in the electromagnetic torque and rotor currents via *PR* current control while the GSC is controlled to suppress the dc link voltage ripples by taking into account the rotor power effect. The proposed control scheme is compared with the dual sequence control scheme . The advantages of the proposed control scheme include the reduced computation and the absence of low pass filters. Matlab/Simulink tests for a 2MW DFIG demonstrate the effectiveness of the control scheme.

Appendix

Parameters of the DFIG and the network:

r_s (pu)	0.00488	X_{ls} (pu)	0.09231
r_r (pu)	0.00549	X_{lr} (pu)	0.09955
X_M (pu)	3.95279	H (pu)	3.5
Z (pu)	0.02+j0.3		

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