CONTROL SCHEME FOR GRID-CONNECTED DFIG WIND TURBINE SYSTEM UNDER GRID VOLTAGE UNBALANCE

Dang Ngoc Khoa[1], Van Tan Luong[1]*, Phan Thi Chieu My[2]

[1]*Ho Chi Minh City University of Food Industry*

[2]*Van Hien University*

*Email: *luongvt@hufi.edu.vn*

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ABSTRACT

A novel control scheme for power converters of doubly-fed induction generator (DFIG) wind turbine system has been proposed to mitigate the current oscillations due to grid voltage unbalance. With this proposed scheme, the current controller is designed in the synchronous reference frame and composed of a proportional integral (PI) controller and a repetitive controller. Thus, the proposed controller gives better performance of the DFIG wind turbine system, compared with the existing dual PI one. The validity of this control scheme has been verified by the simulation of the 2MW-DFIG wind turbine system.

Keywords: Current control, doubly-fed induction generator, repetitive control, unbalanced grid voltage, wind turbine.

1. INTRODUCTION

Nowadays, many speed variable wind turbines with doubly-fed induction generators (DFIGs), which are connected to the grid through back-to-back converters. For the dynamic feature, the DFIG becomes the most popular generator for wind power generation system. The advantage of these facilities is that the power rate of the converters is around 25-30% of the rated generator power. It has been proven that regulating the electrical power production within this range will be a good trade-off between optimal operation and costs. Also, DFIG can supply power to the grid at constant voltage and constant frequency while the rotor can operate at sub-synchronous mode or super synchronous mode. In addition, the generated active and reactive power can be controlled independently [1].

The performance of the DFIG wind turbine system under normal conditions is currently well understood [2, 3]. Practically, both transmission and distribution networks can have voltage imbalance. Unbalanced voltages cause several drawbacks in the DFIG wind turbine [4]. First, due to the low negative-sequence impedance of a DFIG, high negative-sequence currents flow in the stator resulting in overcurrents and overheating. Second, a sustained double-frequency (2ω) pulsation in the electric power and electromagnetic torque is produced by the interaction of negative-sequence voltages with positive-sequence currents. These pulsations are not negligible and generate a high stress in the turbine mechanical system, which can lead to the gearbox fatigue or even to the damage of the rotor shaft, gearbox, or blade assembly [5]. A wind turbine based on DFIG without unbalanced voltage control might be disconnected from the grid during the network voltage unbalance [6, 7].

Several different methods have been suggested to control the current of the generator under unbalanced grid conditions [5, 6, 8-10]. The positive and negative proportional-integral (PI) current controllers in the synchronous dq-axis known as dual PI controllers have been applied in [5, 6, 8, 9], and the proportional resonant (PR) current controller in the stationary α-β axis have been employed in [10]. However, a simple PR controller is effective for a specific component. Also, its transfer function becomes much more complicated and a long execution time is required. On the other hand, it is known that a repetitive control is one of the specific control schemes for which the objective is to remove the errors due to the fundamental and high-order components of the periodic inputs. Thus, a repetitive control strategy is added to the simple PI controller as a compensator for these components. Simulation results for a 2 MW-DFIG wind turbine system are provided to verify the validity of the proposed control scheme.

2. EFEECT OF DFIG IN UNBALANCED VOLTAGE

The configuration of the overall system is shown in Figure 1. It consists of a DFIG wind turbine and back-to-back PWM converters which are connected between the rotor of DFIG and the grid, whereas the the stator side of DFIG is directly connected to the grid.

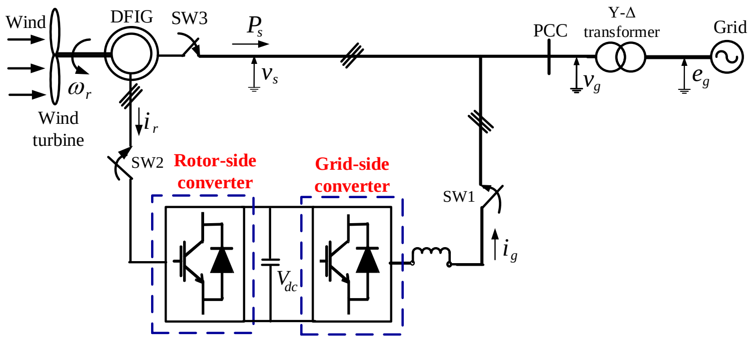

Figure 1. Circuit configuration of DFIG wind turbine system

Figure 2 shows the variable vector F between the $\alpha_s\beta_s$, $\alpha_r\beta_r$ and dq^+, dq^-. For a vector F, the transformations between different reference frames are given as

$$\begin{aligned} &F_{dq}^{+} = F_{\alpha\beta}^{s} e^{-j\omega_e t}, \quad F_{dq}^{-} = F_{\alpha\beta}^{s} e^{j\omega_e t} \\ &F_{dq}^{+} = F_{dq}^{-} e^{-j2\omega_e t}, \quad F_{dq}^{-} = F_{dq}^{+} e^{j2\omega_e t} \\ &F_{dq}^{+} = F_{\alpha\beta}^{r} e^{-j(\omega_e-\omega_r)t}, \quad F_{dq}^{-} = F_{\alpha\beta}^{r} e^{j(-\omega_e-\omega_r)t} \end{aligned} \tag{1}$$

where F represents voltage, current and flux.

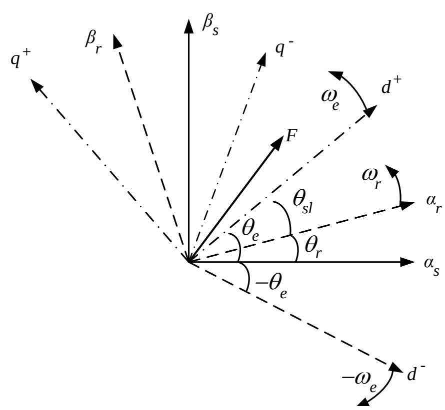

Figure 2. Relation between the $\alpha_s\beta_s$, $\alpha_r\beta_r$ and dq^+, dq^- reference frames.

During voltage imbalance, the voltage, current, and flux all contain positive- and negative-sequence components. Based on equation (1) and shown in Figure 2, *F* can be expressed in terms of positive- and negative-sequence components in the respective positive and negative rotating synchronous frames as

$$F_{dq} = F_{dq}^{+} + F_{dq}^{-} e^{-j2\omega_e t} \tag{2}$$

It is desired that the term of the oscillating component ($2\omega_e$) in (2) must be eliminated for safe operation of the grid-connected wind turbine system.

3. CONTROL OF ROTOR-SIDE CONVERTER

The stator-side apparent power under unbalanced grid voltage can be expressed in terms of the positive and negative sequence components as:

$$\begin{aligned} S_s &= 1.5 v_{dqs}^{s} i_{dqs}^{s*} = 1.5\left(e^{j\omega_e t} v_{dqs}^{+} + e^{j(-\omega_e)t} v_{dqs}^{-}\right)\left(e^{j\omega_e t} i_{dqs}^{+} + e^{j(-\omega_e)t} i_{dqs}^{-}\right)^{*} \\ &= \left[P_{s0} + P_{sc}\cos(2\omega_e t) + P_{ss}\sin(2\omega_e t)\right] + j\left[Q_{s0} + Q_{sc}\cos(2\omega_e t) + Q_{ss}\sin(2\omega_e t)\right] \end{aligned} \tag{3}$$

where P_{s0} and Q_{s0} are the constant (dc) components of the stator active and reactive powers, whereas P_{ss}, P_{sc}, Q_{ss}, and Q_{sc} are the amplitude of the sine and cosine $2\omega_e$ oscillation terms of active and reactive powers, respectively. It is noted that the superscripts of (+), (-), and (*) are used to indicate a positive sequence, negative sequence, and conjugated value, respectively.

Similarly, the electromagnetic torque is obtained as [6]

$$T_e(t) = T_{e0} + T_{ec}\cos(2\omega_e t) + T_{es}\sin(2\omega_e t) \tag{4}$$

Expanding the current and voltage vectors in (3) and (4), the following relations are obtained:

$$\begin{aligned} P_{s0} &= 1,5(v_{ds}^{+} i_{ds}^{+} + v_{qs}^{+} i_{qs}^{+} + v_{ds}^{-} i_{ds}^{-} + v_{qs}^{-} i_{qs}^{-}) \\ P_{sc} &= 1,5(v_{ds}^{+} i_{ds}^{-} + v_{qs}^{+} i_{qs}^{-} + v_{ds}^{-} i_{ds}^{+} + v_{qs}^{-} i_{qs}^{+}) \\ P_{ss} &= 1,5(v_{qs}^{-} i_{ds}^{+} - v_{ds}^{-} i_{qs}^{+} - v_{qs}^{+} i_{ds}^{-} + v_{ds}^{+} i_{qs}^{-}) \\ Q_{s0} &= 1,5(v_{qs}^{+} i_{ds}^{+} - v_{ds}^{+} i_{qs}^{+} + v_{qs}^{-} i_{ds}^{-} - v_{ds}^{-} i_{qs}^{-}) \\ Q_{sc} &= 1,5(v_{qs}^{+} i_{ds}^{-} - v_{ds}^{+} i_{qs}^{-} + v_{qs}^{-} i_{ds}^{+} - v_{ds}^{-} i_{qs}^{+}) \\ Q_{ss} &= 1,5(v_{ds}^{+} i_{ds}^{-} + v_{qs}^{+} i_{qs}^{-} - v_{ds}^{-} i_{ds}^{+} - v_{qs}^{-} i_{qs}^{+}) \end{aligned}$$

It can be seen from (4) that the generator torque due to the grid voltage unbalance includes the dc component (T_{e0}) and ac components (T_{ec}, T_{es}) which have the double frequency ($2\omega_e$) of the grid. In order to eliminate the $2\omega_e$ oscillations in the electromagnetic torque, its oscillating terms in (4) must be nullified (T_{ec} = T_{es} =0). To achieve this, the oscillating components of the reactive powers (Q_{sc}, Q_{ss}) must be controlled to be zero. The reference of the DFIG active power (P_{s0}^{*}) is obtained from a maximum power point tracking (MPPT) algorithm [11]. The reference reactive power (Q_{s0}^{*}) injected by the DFIG can be calculated according to the grid code requirement.

Figure 3 shows the control block diagram of the rotor-side converter under unbalanced grid voltage, which consists of an outer power control loop and an inner current control loop. As for the first loop, the active power is controlled to deliver the generated power from the generator to the grid and the the reactive power (Q_{s0}) is controlled to be zero. The latter loop one allows to regulate the rotor currents for the reduction of the torque oscillation, regardless of the unbalanced grid voltages, based on the PI-repetitive controller.

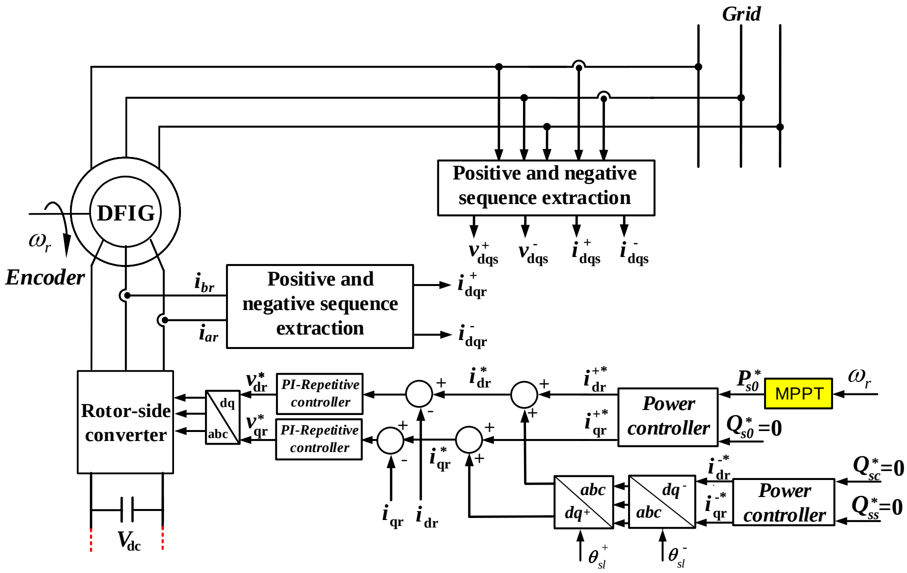

Figure 3. Control diagram of rotor-side converter under unbalance grid voltage.

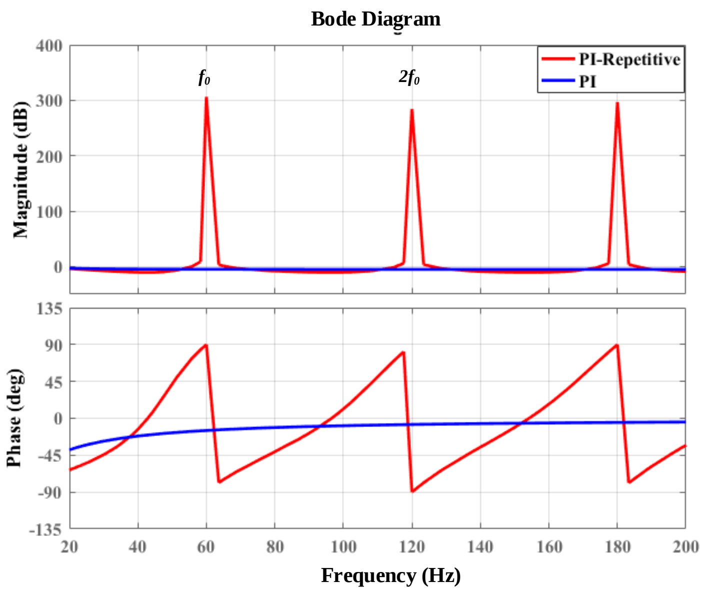

Figure 4. Bode plots for the PI and PI-Repetitive controllers.

In order to investigate the superior characteristics of the PI-Repetitive controller (proposed controller) over the PI controller (conventional controller), Figure 4 describes closed-loop Bode diagram for the conventional controller and the proposed controller given in (5) and (6), respectively.

$$G_{PI}(s) = k_p + \frac{k_i}{s} \tag{5}$$

$$G_{PI-\mathrm{Re}\,petitive}(s) = k_p + \frac{k_i}{s} + k_{re}\frac{e^{-Ts}}{1-e^{-Ts}} \tag{6}$$

As shown in Figure 4, the PI-Repetitive controller designed in the synchronous reference frame produces very high peak gains at the frequencies of 120 Hz, 180 Hz, etc. In this research, the frequency of 120 Hz is mainly considered for the rotor current controller of the DFIG since the oscillating components ($2\omega_e$) are included in the generator torque and power under the unbalanced grid voltage. Thus, the proposed current controller can sufficiently compensate the double frequency components caused by unbalanced grid voltage and it can guarantee a good quality of the generator current despite the unbalanced grid voltage.

4. CONTROL OF GRID-SIDE CONVERTER

The apparent power injected by the grid-side converter to the grid can be partitioned as follows [12, 13]:

$$\begin{aligned} S_g &= 1.5 v_{dqs}^{s} i_{gdqs}^{s*} = 1.5\left(e^{j\omega_e t} v_{dqs}^{+} + e^{j(-\omega_e)t} v_{dqs}^{-}\right)\left(e^{j\omega_e t} i_{gdqs}^{+} + e^{j(-\omega_e)t} i_{gdqs}^{-}\right)^{*} \\ &= \left[P_{g0} + P_{gc}\cos(2\omega_e t) + P_{gs}\sin(2\omega_e t)\right] + j\left[Q_{g0} + Q_{gc}\cos(2\omega_e t) + Q_{gs}\sin(2\omega_e t)\right] \end{aligned} \tag{7}$$

where P_{g0} and Q_{g0} are the constant (dc) components of the grid active and reactive powers, whereas P_{gs}, P_{gc}, Q_{gs}, and Q_{gc} are the amplitude of the sine and cosine $2\omega_e$ oscillation terms of active and reactive powers, respectively.

From (7), the powers (P_{g0}, Q_{g0}, P_{gc}, P_{gs}) can be represented in a matrix form as

$$\begin{bmatrix} P_{g0} \\ Q_{g0} \\ P_{gs} \\ P_{gc} \end{bmatrix} = 1.5 \begin{bmatrix} v_{ds}^{+} & v_{qs}^{+} & v_{ds}^{-} & v_{qs}^{-} \\ v_{qs}^{+} & -v_{ds}^{+} & v_{qs}^{-} & -v_{ds}^{-} \\ v_{qs}^{-} & -v_{ds}^{-} & -v_{qs}^{+} & v_{ds}^{+} \\ v_{ds}^{-} & v_{qs}^{-} & v_{ds}^{+} & v_{qs}^{+} \end{bmatrix} \begin{bmatrix} i_{gd}^{+} \\ i_{gq}^{+} \\ i_{gd}^{-} \\ i_{gq}^{-} \end{bmatrix} \tag{8}$$

The second-order components of power (P_{gs}, P_{gc}) due to the unbalanced grid voltage fluctuates not only the DC-link capacitor power but also the real power delivered to the grid. These two components are controlled to zero to eliminate the power fluctuations. The real power reference (P_{g0}^{*}) is the product of the dc voltage controller output and the dc voltage reference. Thus, the positive- and negative-sequence components of the current references are expressed as

$$\begin{bmatrix} i_{gd}^{+*} \\ i_{gq}^{+*} \\ i_{gd}^{-*} \\ i_{gq}^{-*} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} v_{ds}^{+} & v_{qs}^{+} & v_{ds}^{-} & v_{qs}^{-} \\ v_{qs}^{+} & -v_{ds}^{+} & v_{qs}^{-} & -v_{ds}^{-} \\ v_{qs}^{-} & -v_{ds}^{-} & -v_{qs}^{+} & v_{ds}^{+} \\ v_{ds}^{-} & v_{qs}^{-} & v_{ds}^{+} & v_{qs}^{+} \end{bmatrix}^{-1} \begin{bmatrix} P_{g0}^{*} \\ Q_{g0}^{*} \\ 0 \\ 0 \end{bmatrix} \tag{9}$$

Figure 5 shows the control block diagram of the grid-side converter under unbalanced grid voltage, which consists of an outer DC-link voltage control loop and an inner current control loop. The dq-axis current controller is employed as in the rotor-side converter, which depend on the PI-repetitive control method.

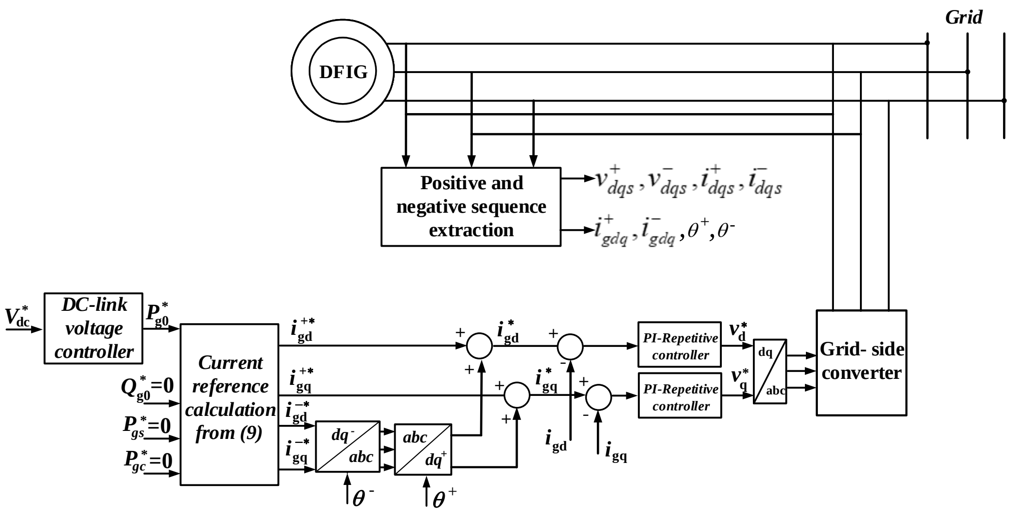

Figure 5. Control diagram of grid-side converter under unbalance grid voltage.

5. SIMULATION RESULTS

To verify the feasibility of the proposed method, PSCAD simulation has been carried out for a 2 MW-DFIG wind turbine system. For the wind turbine: R = 44 m; $\rho = 1.225$ kg/m^3; $\lambda_{opt} = 8$; $J_t = 5.67\text{x}10^6$ kg·m^2. For the DFIG: the grid voltage is 690 V/60 Hz; the rated power is 2 MW; $R_s = 0.00488$ pu; $R_r = 0.00549$ pu; $L_{ls} = 0.0924$ pu; $L_{lr} = 0.0995$ pu; and $J_g = 200$ kg·m^2. For 2 MW-DFIG system, 14% unbalanced voltage sag is applied at the grid side for investigation.

Figure 6 shows the control performance of the DFIG at the rotor-side converter for a grid unbalanced voltage sag. The wind speed is assumed to be constant (10.5 m/s) since the pattern of variable wind speed can not produce a remarkable effect during the short time duration of the fault. The fault condition is 14% sag in the grid A-phase voltage for 0.5 s which is between 1.5 s and 2 s.

Figure 6A shows the performance of the DFIG using dual PI control method for the rotor currents, in case of the unbalanced grid condition [6]. As can be seen from Figure 6A(b), the oscillations of the dq-axis positive-sequence rotor currents become large. Similarly, the stator active and reactive powers, the generator torque as illustrated in Figure 6A(c), (d) and (f), respectively contain the significant pulsations at 120 Hz. As shown in Figure 6A(e), the generator speed is much oscillated during the grid fault.

Figure 6B shows the DFIG performance using the proposed control method for the rotor currents under the grid fault condition. With the current control based on PI-Repetitive controller, the oscillations of the positive-sequence rotor currents in dq-axis, as shown in Figure 6B(b) are significantly suppressed. Accordingly, the stator active and reactive power oscillations are also mitigated, as shown in Figure 6B(c) and Figure 6B(d), respectively. Also, the oscillations of the generator speed and torque are considerably reduced, as shown in Figure 6B(e) and (f), respectively. By comparison, the rotor current control method based on PI-Repetitive controller gives less oscillations than dual PI controller.

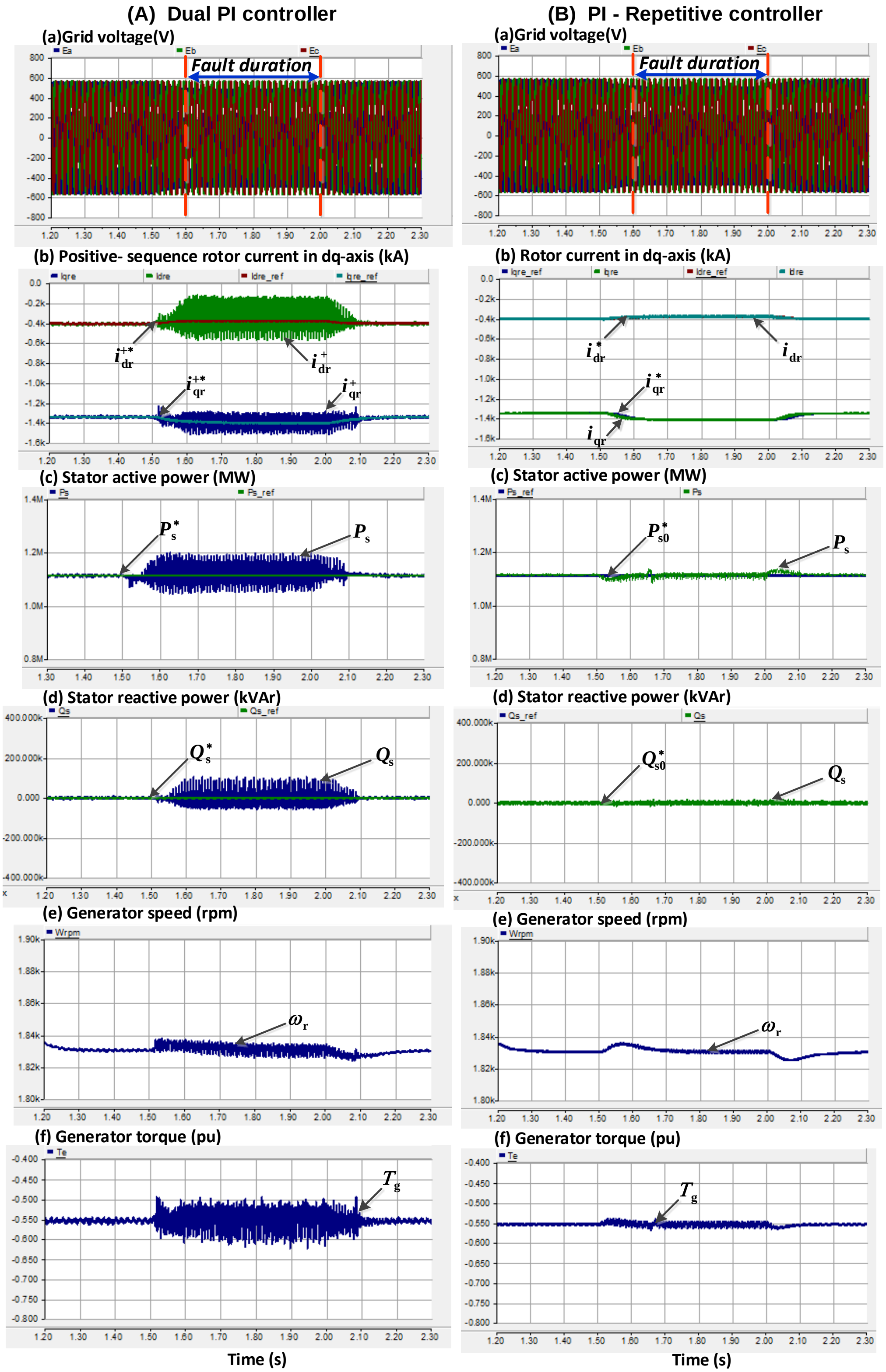

Figure 6. Control performance of rotor-side converter for grid phase-A voltage sag (14%) in 2 cases: (A) Dual PI control [6]. (B) Proposed method. (a) Grid voltage. (b) Rotor current. (c) Stator active power. (d) Stator reactive power. (e) Generator speed. (f) Generator torque.

Figure 7 shows the control performance of the DFIG at the grid-side converter for 14% grid A-phase voltage sag. Figure 7A and 7B show the performance of the DFIG using dual PI control method (see [6]) and PI-Repetitive control one for the grid currents, respectively. As can be clearly seen in Figure 7A(b), the DC-link voltage is controlled to follow its reference well. However, the oscillations of the DC-link voltage is high and its variation is 12.5%, compared with the reference DC-link voltage. Likewise, the oscillations of the positive-sequence rotor currents in dq-axis, as shown in Figure 7A(c) are also increased. By applying the PI-Repetitive controller for grid currents, the DC-link voltage and grid current oscillations are significantly reduced, as shown in Figure 7B(b) and (c), respectively. By comparison, the grid current control method based on PI-Repetitive controller gives better performance, compared with dual PI controller.

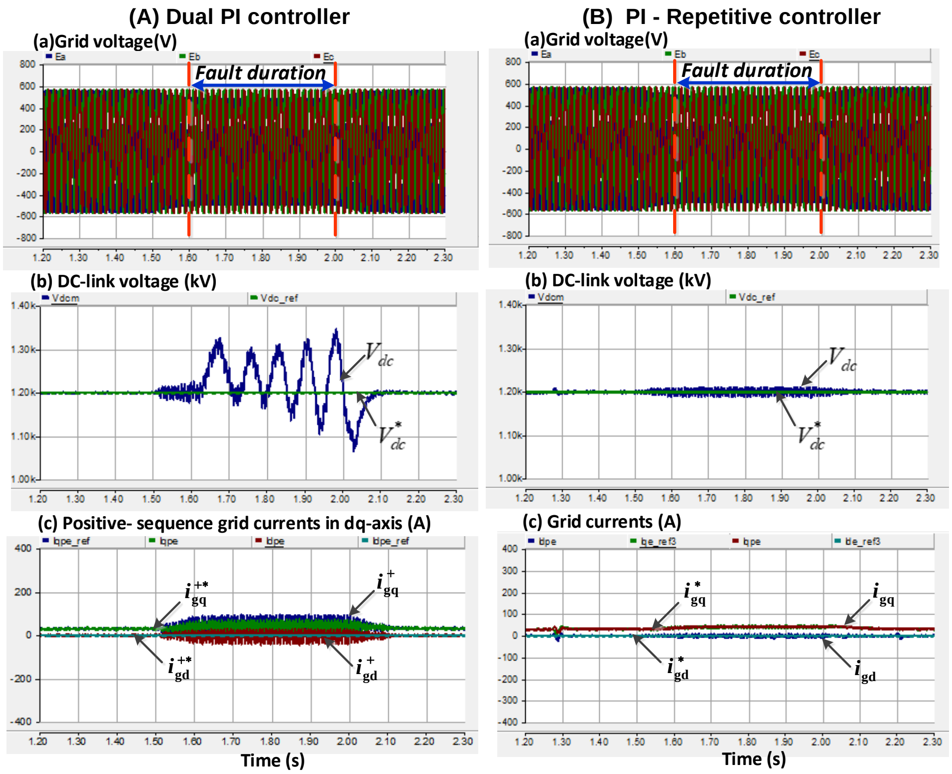

Figure 7. Control performance of grid-side converter for grid phase-A voltage sag (14%) in 2 cases: (A) Dual PI control [6]. (B) Proposed method. (a) Grid voltage. (b) DC-link voltage. (c) Grid current.

6. CONCLUSION

This paper has presented a current control scheme based on the PI-Repetitive controllers for grid-connected DFIG wind turbine system under unbalanced grid conditions. The dynamic response of controlling the DFIG to the transient grid unbalance has been analyzed and the current control scheme for both grid-side converter and rotor-side converter has been introduced. Compared with the existing unbalanced control method like dual PI control, the proposed one provides better performances for both grid and rotor currents, from which the generator torque and power oscillations are much reduced. The validity of the proposed one is verified by the simulation results for the 2 MW-DFIG wind turbine system under unbalanced grid voltage conditions.

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TÓM TẮT

CHIẾN LƯỢC ĐIỀU KHIỂN KẾT NỐI LƯỚI CỦA HỆ THỐNG TUA-BIN GIÓ DÙNG MÁY PHÁT DFIG KHI ĐIỆN ÁP LƯỚI KHÔNG CÂN BẰNG

Đặng Ngọc Khoa[1], Văn Tấn Lượng[1,*], Phan Thị Chiêu Mỹ[2]
[1]*Trường Đại học Công nghiệp Thực phẩm TP.HCM*
[2]*Trường Đại học Văn Hiến*
*Email: *luongvt@hufi.edu.vn*

Chiến lược điều khiển các bộ chuyển đổi công suất của hệ thống tua-bin gió dùng máy phát không đồng bộ nguồn kép (DFIG) được đề xuất để giảm thiểu độ dao động dòng điện do sự không cân bằng điện áp lưới gây ra. Bộ điều khiển dòng điện được thiết kế trong hệ tọa độ xoay và bao gồm bộ điều khiển tích phân - tỷ lệ (PI) và bộ điều khiển lặp lại. Do đó, bộ điều khiển đề xuất cho kết quả vận hành tốt hơn cho hệ thống tua-bin gió dùng máy phát DFIG, so với bộ điều khiển PI kép hiện có. Tính hợp lý của chiến lược điều khiển này đã được xác minh bằng kết quả mô phỏng hệ thống tua-bin gió 2MW-DFIG.

Từ khóa: Điều khiển dòng điện, máy phát không đồng bộ nguồn kép, điều khiển lặp lại, điện áp lưới không cân bằng, tua-bin gió.