NONLINEAR CONTROL OF DYNAMIC VOLTAGE RESTORER TO IMPROVE LVRT CAPABILITY IN WIND TURBINE SYSTEMS

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ABSTRACT

This paper proposes a nonlinear control of dynamic voltage restorer (DVR) based on a feedback linearization (FL) theory to improve a low-voltage ride-through (LVRT) capability of a doubly fed induction generator (DFIG) wind turbine system. First, the nonlinear model of the system including LC filter is obtained in the d-q synchronous reference frame. Then, the controller design of the linearized model is performed by the multi-input multi-output feedback linearization. The simulation results for the 2 MW-DFIG wind turbine system with the DVR compensation at grid faults gives as good performance as those without grid faults.

Keywords: Doubly-fed induction generator, dynamic voltage restorer, feedback linearization theory, voltage sag, wind turbine.

1. INTRODUCTION

Nowadays, wind energy is one of the fastest growing industries and it will continue to grow worldwide, as many countries have plans for future development. With rapid increase in penetration of wind power in electric network, the problems related to system operation, such as voltage variations, grid voltage unbalance, and grid instability may be derived. Thus, they must have the same operational behavior with several control tasks in both normal and fault conditions. One of these control tasks is the low-voltage ride-through (LVRT) capability.

The grid codes require the LVRT capability of the wind turbine system. For some national grid codes [1], the wind power systems should stay connected to the grid for the grid fault conditions. In the power system where the wind power generation is of a major portion, the grid will experience the power outage if the wind farms trip off. A diagram of the LVRT requirements in which wind turbines should remain connected for voltage sags is shown in Figure 1 [1].

A doubly fed induction generator (DFIG) is essentially a wound-rotor induction generator with slip rings, in which the stator is directly connected to the grid, and the rotor is interfaced through back-to-back PWM converters. Normally, the rating capacity of the converters could be only $25\% \sim 30\%$ of the generation power [2].

A modern wind power system demands the wind turbines kept connected to the grid during the grid faults, especially the voltage sags. When there are the grid voltage dips, the rotor voltage can be increased, which may result in the overvoltage or overcurrent of the rotor-side converter (RSC). To protect the converter as well as achieve the LVRT successfully, the crowbar has been used in order to absorb the inrush energy [3 - 6]. However, since these circuits are added to the system, the cost is increased and the system and control become complicated. Also, a static synchronous compensator (STATCOM) has been suggested to support with the uninterrupted operation of the DFIG during the grid faults [7-9]. In this method, the STATCOM that is installed at the point of common coupling (PCC) can be employed to supply much reactive power to the grid. However, the STATCOM is not used alone for the DFIG ride-through capability when the grid fault happens. On the other hand, it should be used together with the crowbar circuit which protects the RSC from the rotor over-current under the grid fault. An energy storage system (ESS) which has been applied to the wind generation systems, can offer fault ride-through capability [10]. For this, the power is absorbed from the system or released to the grid for both normal and fault conditions by using the ESS. Meanwhile, the DC-link voltage is controlled at the grid-side converter (GSC) in both normal condition and grid sags and the power mismatched between the turbine and the grid-side are stored in the inertia by increasing the generator speed. However, the amount of energy stored in the turbine inertia is not so large, when the generator operates near the rated speed before the grid sags happen. Also, a braking chopper (BC) which has low cost and simple control has been applied for the LVRT [11]. However, the power quality at the output of the wind turbine systems is not much improved because the BC can just dissipate the power without capability of returning the power to the grid. In one way, a scheme consists of the ESS and BC which are connected to the DC-link side of the back-to-back converter in DFIG wind turbine system [12]. The DC-link voltage is controlled by using the ESS, while the GSC is considered as STATCOM to regulate the reactive current according to the grid code requirement. Nevertheless, the cost of the ESS is so high to solve this problem practically. In another way, series voltage injection approach based on dynamic voltage restorer (DVR) has been applied for the LVRT capabilities [13]. With this method, the fault ride-through can be obtained effectively. However, a typical proportional integral (PI) controller does not work well for controlling the AC signals.

To overcome this problem, a DVR using a feedback linearization technique has been suggested for the LVRT capability in the DFIG wind power system working in the grid fault conditions. Thus, the nonlinear controller designed becomes simpler and gives good performance of the system. Simulation results for a 2 MW-DFIG wind turbine system are provided to verify the validity of the proposed control scheme.

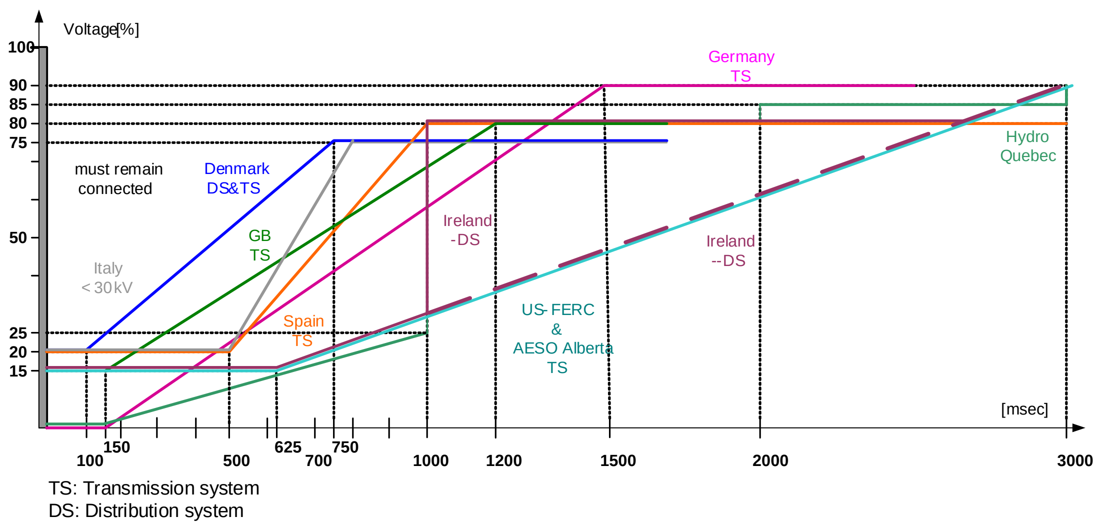

Figure 1. National grid codes [1].

2. SYSTEM MODELING

The configuration of the overall system is shown in Figure 2. It comprises a DFIG wind turbine and back-to-back PWM converters which are connected between the rotor of DFIG and the grid. The DVR is a three-phase voltage source converter (VSC) connected in series with the power line via the transformers to inject the compensation voltages. As can be seen, an LC filter is connected between the VSC and the series transformer. The DC-link capacitor of the DVR is connected to the DFIG side through three phase diode rectifier and charged from a passive filter.

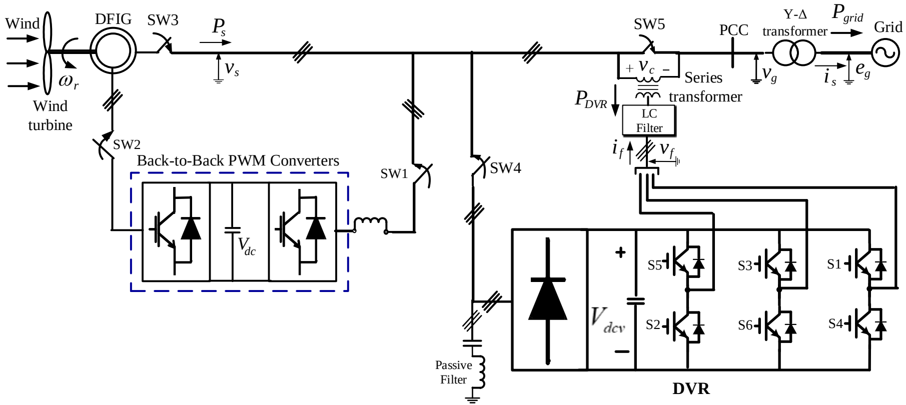

Figure 2. DFIG wind turbine system within using DVR.

The modeling of the DVR is briefly described in this section, in which the components of the positive and negative-sequence currents and voltages of the DVR can be expressed in synchronous d-q reference frame as follows [13-14]:

$$\begin{cases} \dot{V}_{cq}^{+} = \dfrac{1}{C} I_{fq}^{+} - \omega_e \dfrac{C_f}{C} V_{cd}^{+} - \dfrac{1}{C} I_{sq}^{+} \\ \dot{I}_{fq}^{+} = \dfrac{1}{L_f} V_{fq}^{+} - \omega_e I_{fd}^{+} - \dfrac{1}{L_f} V_{cq}^{+} \\ \dot{V}_{cd}^{+} = \dfrac{1}{C} I_{fd}^{+} + \omega_e \dfrac{C_f}{C} V_{cq}^{+} - \dfrac{1}{C} I_{sd}^{+} \\ \dot{I}_{fd}^{+} = \dfrac{1}{L_f} V_{fd}^{+} + \omega_e I_{fq}^{+} - \dfrac{1}{L_f} V_{cd}^{+} \end{cases} \tag{1}$$

$$\begin{cases} \dot{V}_{cq}^{-} = \dfrac{1}{C} I_{fq}^{-} + \omega_e \dfrac{C_f}{C} V_{cd}^{-} - \dfrac{1}{C} I_{sq}^{-} \\ \dot{I}_{fq}^{-} = \dfrac{1}{L_f} V_{fq}^{-} + \omega_e I_{fd}^{-} - \dfrac{1}{L_f} V_{cq}^{-} \\ \dot{V}_{cd}^{-} = \dfrac{1}{C} I_{fd}^{-} - \omega_e \dfrac{C_f}{C} V_{cq}^{-} - \dfrac{1}{C} I_{sd}^{-} \\ \dot{I}_{fd}^{-} = \dfrac{1}{L_f} V_{fd}^{-} - \omega_e I_{fq}^{-} - \dfrac{1}{L_f} V_{cd}^{-} \end{cases} \tag{2}$$

where $V_{cd}^{+}, V_{cq}^{+}, V_{cd}^{-}$, and V_{cq}^{-} are the *dq*-components of the voltage across the filter capacitor of the series VSC. V_{fd}^{+}, V_{fq}^{+}, V_{fd}^{-}, and V_{fq}^{-} are the *dq*-components of the inverter output voltage of the series VSC. I_{sd}^{+}, I_{sq}^{+}, I_{sd}^{-}, and I_{sq}^{-} are *dq* components of the grid current. I_{fd}^{+}, I_{fq}^{+}, I_{fd}^{-}, and I_{fq}^{-} are *dq*-components of the filter inductor current of the series VSC. It is noted that the subscripts "+" and "-" denote the positive and negative-sequence components, respectively.

From (1), a state-space modeling of the system written in the positive sequence-components is derived as follows:

$$\begin{bmatrix} \dot{V}_{cq}^{+} \\ \dot{I}_{fq}^{+} \\ \dot{V}_{cd}^{+} \\ \dot{I}_{fd}^{+} \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\dfrac{\omega_e C_f}{C} & 0 \\ -\dfrac{1}{L_f} & 0 & 0 & 0 \\ \dfrac{\omega_e C_f}{C} & 0 & 0 & 0 \\ 0 & 0 & -\dfrac{1}{L_f} & 0 \end{bmatrix} \begin{bmatrix} V_{cq}^{+} \\ I_{fq}^{+} \\ V_{cd}^{+} \\ I_{fd}^{+} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \dfrac{1}{L_f} & 0 \\ 0 & 0 \\ 0 & \dfrac{1}{L_f} \end{bmatrix} \begin{bmatrix} V_{fq}^{+} \\ V_{fd}^{+} \end{bmatrix} + \begin{bmatrix} -\dfrac{1}{C} I_{sq}^{+} \\ 0 \\ -\dfrac{1}{C} I_{sd}^{+} \\ 0 \end{bmatrix} \quad (3)$$

3. PROPOSED DVR CONTROL SCHEME

3.1. Reference of compensation voltage

The reference of the compensation voltage across the series transformer injected by the DVR can be expressed as:

$$\begin{bmatrix} v_{ca}^{*} \\ v_{cb}^{*} \\ v_{cc}^{*} \end{bmatrix} = \begin{bmatrix} v_{ga,\,presag} - v_{ga} \\ v_{gb,\,presag} - v_{gb} \\ v_{gc,\,presag} - v_{gc} \end{bmatrix} \quad (4)$$

where $v_{ga,\,presag}$, $v_{gb,\,presag}$ and $v_{ga,\,presag}$ are the voltages across the low-voltage side of the Y-Δ transformer before the sag; v_{ga}, v_{gb} and v_{gc} are the voltages after the sag.

3.2. DVR control scheme using feedback linearization theory

The fundamental principle of using the FL technique is to linearize the nonlinear system by differentiating the outputs of the system until the input variables appear [13-14].

A multi-input multiple-output system can be considered as:

$$\dot{x} = f(x) + gu \quad (5)$$

$$y = h(x) \quad (6)$$

where *x* is the state vector, *u* is the control input, *y* is the output, *f* and *g* are the smooth vector fields, respectively, and *h* is the smooth scalar function.

The nonlinear model of the DVR in (3) is expressed in (5) and (6) as:

$$x = \begin{bmatrix} V_{cq}^{+} & I_{fq}^{+} & V_{cd}^{+} & I_{fd}^{+} \end{bmatrix}^T ; u = \begin{bmatrix} V_{fq}^{+} & V_{fd}^{+} \end{bmatrix}^T ; y = \begin{bmatrix} V_{cq}^{+} & V_{cd}^{+} \end{bmatrix}^T$$

To generate an explicit relationship between the outputs $y_{i=1,2}$ and the inputs $u_{i=1,2}$, each output is differentiated until a control input appears.

$$\begin{bmatrix}\ddot{y}_1\\ \ddot{y}_2\end{bmatrix}=A(x)+E(x)\begin{bmatrix}u_1\\ u_2\end{bmatrix} \tag{7}$$

Then, the control law is given as

$$\begin{bmatrix}V_{fq}^*\\ V_{fd}^*\end{bmatrix}=\begin{bmatrix}u_1\\ u_2\end{bmatrix}=E^{-1}(x)\left[-A(x)+\begin{bmatrix}v_1\\ v_2\end{bmatrix}\right] \tag{8}$$

where $A(x)=\begin{bmatrix}\frac{\omega_e}{C}\left(1+\frac{C_f}{C}\right)I_{fd}^+ +\frac{1}{C}\left(\frac{1}{L_f}+\frac{\omega_e^2C_f^2}{C}\right)V_{cq}^+ +\frac{1}{C}\dot{I}_{sq}^+ -\frac{\omega_eC_f}{C^2}I_{sd}^+\\ -\frac{\omega_e}{C}\left(1+\frac{C_f}{C}\right)I_{fq}^+ +\frac{1}{C}\left(\frac{1}{L_f}+\frac{\omega_e^2C_f^2}{C}\right)V_{cd}^+ +\frac{1}{C}\dot{I}_{sd}^+ +\frac{\omega_eC_f}{C^2}I_{sq}^+\end{bmatrix}$; $E^{-1}(x)=\begin{bmatrix}L_fC & 0\\ 0 & L_fC\end{bmatrix}$ and v_1 and v_2 are new control inputs.

To eliminate this tracking error in the presence of parameters variations, integral controls are added to the tracking controller. Thus, the new control inputs are given by

$$\begin{bmatrix}v_1\\ v_2\end{bmatrix}=\begin{bmatrix}\ddot{y}_1^*+k_{11}\dot{e}_1+k_{12}e_1+k_{13}\int e_1\\ \ddot{y}_2^*+k_{21}\dot{e}_2+k_{22}e_2++k_{23}\int e_2\end{bmatrix} \tag{9}$$

where $e_1=y_1^*-y_1$, and $e_2=y_2^*-y_2$, y_1^* and y_2^* are the reference values of the y_1 and y_2, respectively, k_{11}, k_{12}, k_{21}, and k_{22} are controller gains.

The voltage references obtained from (8) and (9), are expressed as

$$\begin{bmatrix}u_1\\ u_2\end{bmatrix}=\begin{bmatrix}L_fC\left[v_1+\frac{\omega_e}{C}\left(1+\frac{C_f}{C}\right)I_{fd}^+ +\frac{1}{C}\left(\frac{1}{L_f}+\frac{\omega_e^2C_f^2}{C}\right)V_{cq}^+ +\frac{1}{C}\dot{I}_{sq}^+ -\frac{\omega_eC_f}{C^2}I_{sd}^+\right]\\ L_fC\left[v_2-\frac{\omega_e}{C}\left(1+\frac{C_f}{C}\right)I_{fq}^+ +\frac{1}{C}\left(\frac{1}{L_f}+\frac{\omega_e^2C_f^2}{C}\right)V_{cd}^+ +\frac{1}{C}\dot{I}_{sd}^+ +\frac{\omega_eC_f}{C^2}I_{sq}^+\right]\end{bmatrix} \tag{10}$$

The tracking errors can be successfully converged to zero when the gains of tracking controllers are properly designed. A pole placement technique is used to place all poles of the system at specific locations in the left-half side of the complex plane resulting in a stable system. Thus, $k_{11}=k_{21}=5.1x10^3$; $k_{12}=k_{22}=8.3x10^6$ and $k_{13}=k_{23}=4.8x10^9$ are determined by assigning the desired poles with a consideration of satisfactory performance in terms of the percent overshoot, settling time, and rise time.

The block diagram of the proposed control is shown in Figure 3, in which the components of the positive-sequence voltages in the dq-axis are separately controlled by using the FL. Meanwhile, the components of the negative-sequence voltages in the dq-axis are regulated, based on the PI controller. Then, the outputs of the FL control (V_{fdq}^{+*}) and the PI control (V_{fdq}^{-*}) are transformed to the voltage references in three-phase abc reference frame, employed for the space vector pulse-width modulation (SVPWM).

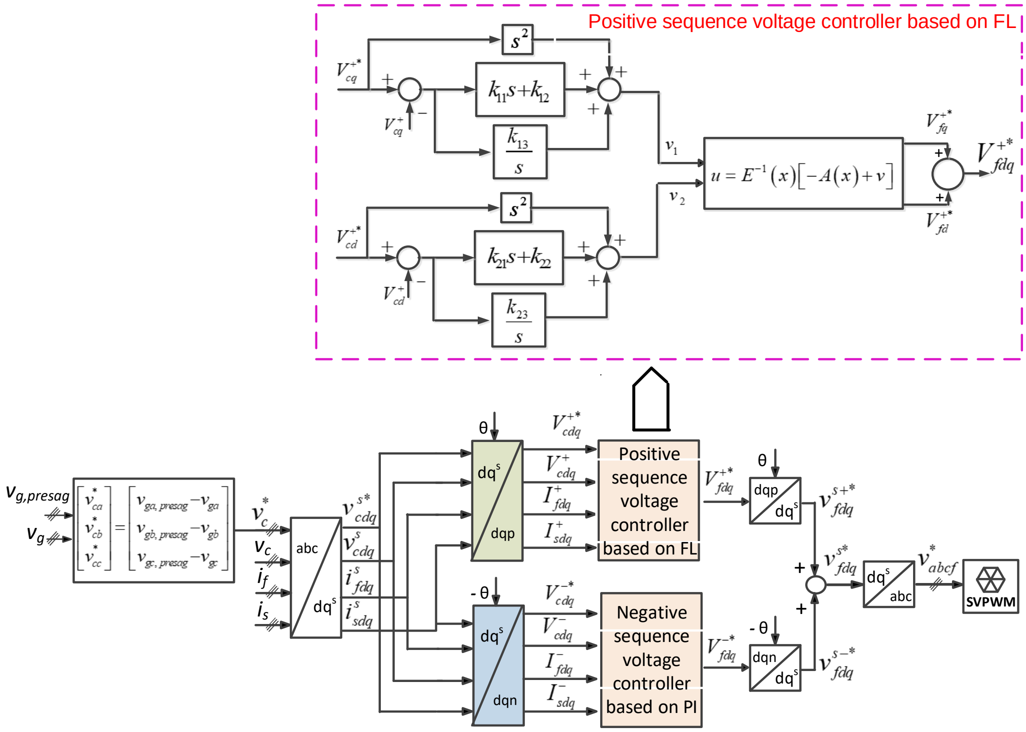

Figure 3. Proposed control block diagram of DVR.

4. 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; ρ = 1.225 kg/m^3; λ_{opt} = 8. 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 = 200 kg·m^2. The grid voltage is 690 V and 60 Hz. For the DVR: the DC-link capacitor is 8200 μF; the inverter output LC filter is 0.2 mH and 8200 μF.

Figure 4 shows the system performance for unbalanced grid voltage fault without using DVR system, where the wind speed is assumed to be constant (11 m/s) for easy investigation. The fault condition is 40% sag in both the grid A-phase and C-phase voltage and 100% sag in the grid C-phase voltage for 0.1 s which is between 1.4 s and 1.5 s. Due to the grid unbalanced voltage sag (see Figure 4(a)), the DC-link voltage, stator current, rotor current, generator speed, and generator torque are illustrated from Figure 4(b) to 4(f), respectively. As can be clearly seen, almost all of the waveforms give high ripples under the grid voltage sag.

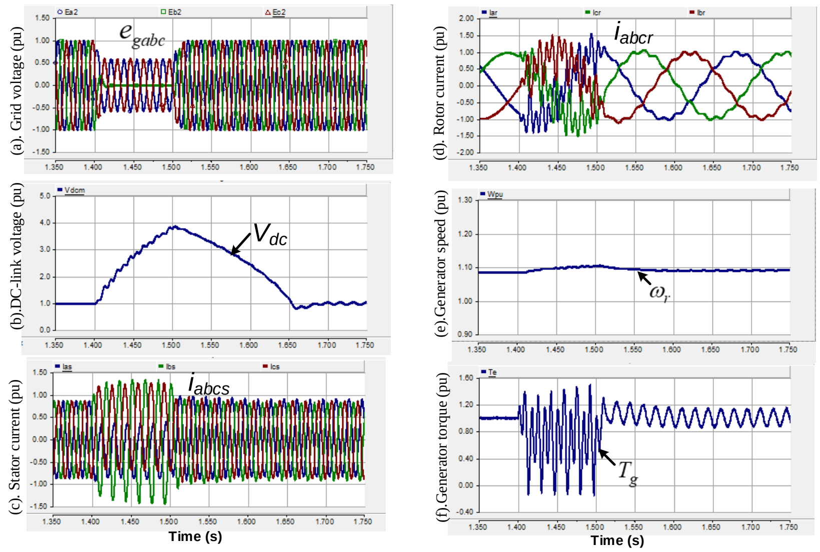

Figure 4. Performance of DFIG wind turbine system for unbalanced voltage sag (in pu).

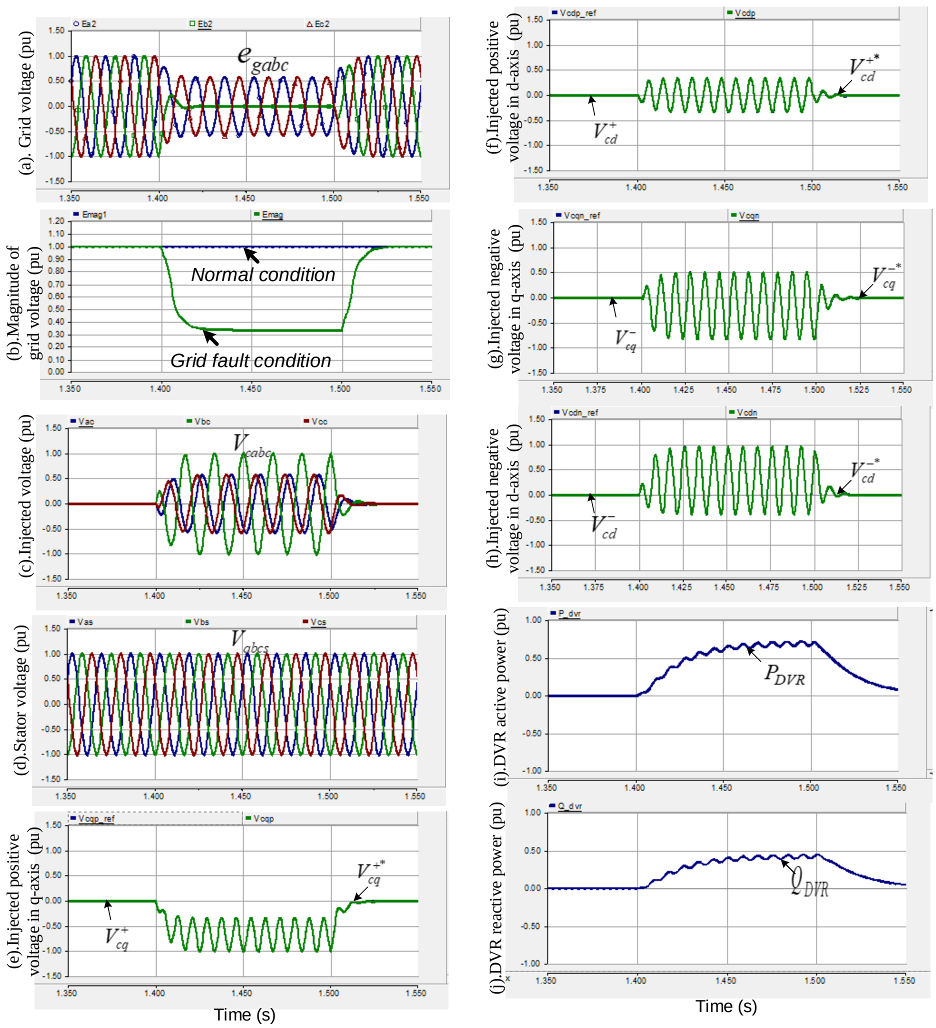

Figure 5. Performance of DVR system for unbalanced voltage sag (in pu).

Figure 5 shows the performance of DVR system under three-phase unbalanced voltages. When the unbalanced voltage sag occurs in Figure 5 (a), the magnitude of the grid voltage is illustrated in Figure 5 (b). According to several national grid codes as shown in Figure 1, it is guaranteed that the DFIG wind turbine system can stay connected to the grid during the unbalanced voltage sag. The compensation voltages in Figure 5 (c) are injected by the DVR system. Also, the stator voltages in Figure 5 (d) are kept at the rated value. It can be obviously seen from Figure 5 (e) and (f) that the dq-axis positive sequence voltages of the DVR are AC values during the grid fault. Since the type of the fault is unbalanced, the negative-sequence components of the grid voltage in dq-axis are produced, as illustrated in Figure 5 (g) and (h). The active and reactive powers produced from the DVR are shown in Figure 5 (i) and (j), respectively. Without compensation, the stator and rotor currents, and torque oscillate much, as illustrated in Figure 4(c), 4(d) and 4(f), respectively. However, they are kept almost constant with compensation.

Figure 6 shows the performance of DFIG wind turbine system under three-phase unbalanced voltages. It is clear from Figure 6 that all quantities of the DFIG with the DVR compensation at grid faults can be kept the same as those without grid faults since the DFIG operation is not affected by the grid faults. Thus, the proposed method achieves the good operation for the DFIG wind turbine system under the grid faults.

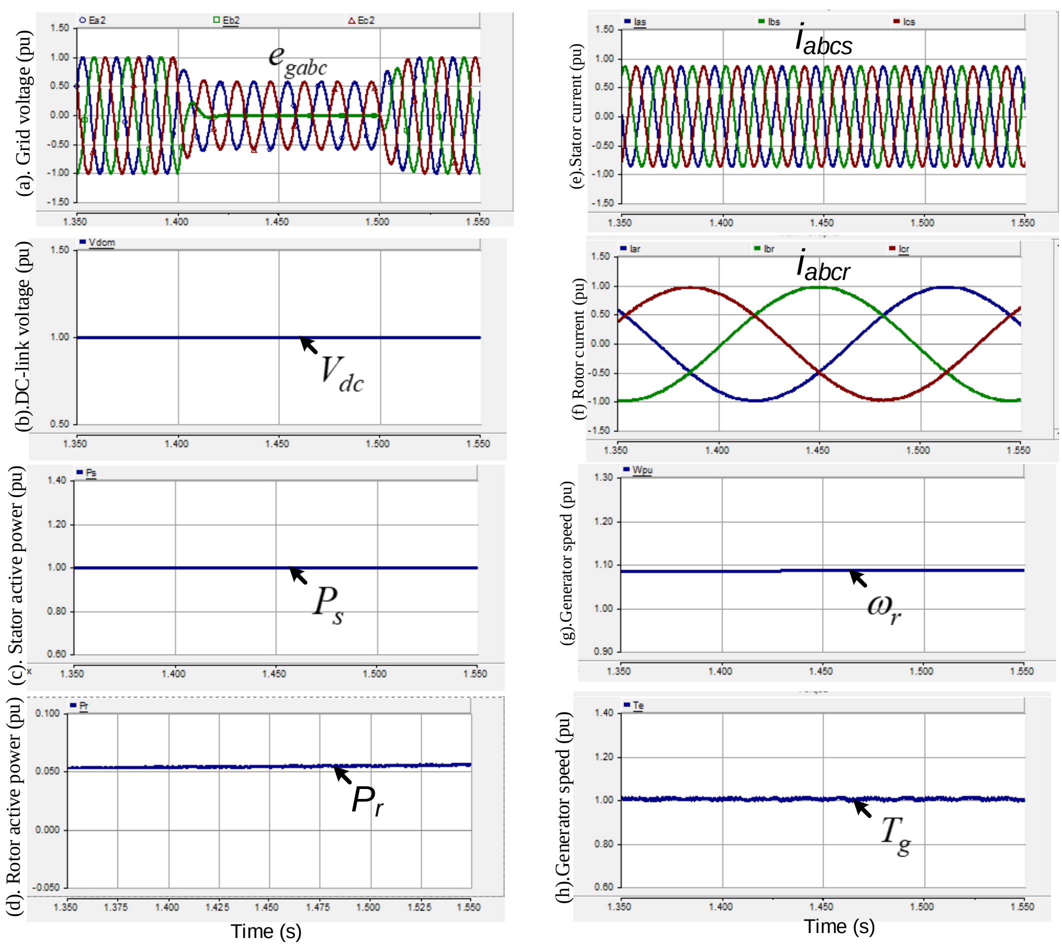

Figure 6. Performance of DFIG wind turbine system for unbalanced voltage sag (in pu).

5. CONCLUSION

This paper has presented a nonlinear control of dynamic voltage restorer to improve a low-voltage ride-through of a doubly fed induction generator wind turbine system under grid voltage sag conditions. With the proposed method, nonlinear model of DVR system based on a feedback linearization theory is firstly linearized, not by small signal analysis. Then, the proposed DVR control method can achieve the good operation for the DFIG wind turbine system under all kinds of grid faults, depending on the design of the system parameters. The effectiveness of the proposed DVR compensation scheme 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

ĐIỀU KHIỂN PHI TUYẾN CỦA BỘ PHỤC HỒI ĐIỆN ÁP ĐỘNG ĐỂ CẢI THIỆN KHẢ NĂNG LVRT TRONG HỆ THỐNG TUA-BIN GIÓ

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Bài báo này đề xuất điều khiển phi tuyến của bộ phục hồi điện áp động (DVR) dựa trên lý thuyết tuyến tính hóa phản hồi (FL) để cải thiện khả năng lướt qua điện áp thấp (LVRT) của hệ thống tua-bin gió máy phát không đồng bộ nguồn kép (DFIG). Đầu tiên, mô hình phi tuyến của hệ thống bao gồm bộ lọc LC đạt được trong hệ tọa độ quay d-q. Sau đó, việc thiết kế bộ điều khiển của mô hình tuyến tính được thực hiện bằng việc tuyến tính hóa hồi tiếp đa đầu ra, đa đầu vào. Kết quả mô phỏng đã thể hiện rằng phương pháp đề xuất cho kết quả vận hành tốt đối với hệ thống tua-bin gió máy phát DFIG công suất 2 MW trong điều kiện độ võng điện áp lưới.

Từ khóa: Máy phát không đồng bộ nguồn kép, bộ phục hồi điện áp động, lý thuyết tuyến tính hóa hồi tiếp, độ võng điện áp lưới, tua-bin gió.