LOW-VOLTAGE RIDE-THROUGH TECHNIQUE FOR DFIG WIND TURBINE SYSTEM

Van Tan Luong*, Nguyen Phu Cong

Ho Chi Minh City University of Food Industry

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

Received: 27 February 2020; Accepted: 10 April 2020

ABSTRACT

This paper proposes a low-voltage ride-through (LVRT) technique for a doubly fed induction generator (DFIG) wind turbine (WT) system. With the proposed method, both shunt and series voltage-source converters employed, enable to compensate a voltage response of the system simultaneously during the grid faults. For the series voltage source converter (VSC), a control algorithm including dual voltage controllers is performed for the two sequence components in the *dq* synchronous reference frame. As for shunt VSC, a control algorithm consists of an inner current control loop and an outer DC-link voltage control loop, in which the current control loop is carried out in the *dq* synchronous reference frame. The simulation results for 2 MW-DFIG wind turbine system with the compensation at the grid faults gives as good performance as those without grid faults.

Keywords: Doubly-fed induction generator, grid fault, low-voltage ride –through, positive and negative sequence, wind turbine.

1. INTRODUCTION

The ever increasing penetration level of wind energy into the power grid is reshaping the way that wind farms are operated in. During certain periods of large wind generation and light load conditions, the power in the system can be covered by the wind. The share of wind power related to the stiffness of the electric grid and other power plants is reaching the level in which wind power may cause the issues of grid voltage instability to system operators. Wind farms can not be considered as a simple energy source anymore. Now the power plants must be operated to supply reactive power to keep connected grid continuously during system faults as well as to adapt their control to the requirements of the system. The most important need for wind farms, especially with DFIGs is the fault ride-through capability. Wind farms connected to a high-voltage transmission system have to remain connected when there is a voltage dip in the grid, or a sudden disconnection of a great amount of wind power may exacerbate the voltage dip, with severe consequences [1, 2].

A DFIG is mainly a wound-rotor induction generator with slip rings, in which the stator is directly connected to the grid, and the rotor is connected to the grid through back-to-back converters. Since they only handle the slip energy of the DFIG, the rating capacity of the converters could be only 25-30% of the generation power [3].

The modern wind power system requires the wind turbines to stay connected to the grid during the grid sags. When the grid voltage dips occur, the increased rotor voltage would be induced by the complex electromagnetic interaction in the DFIG, which may result in the overvoltage or overcurrent of the rotor-side converter (RSC). To protect the converter as well as achieve LVRT successfully, the crowbar has been used so that the inrush energy is absorbed [4-7].

However, these added circuits increase the cost and complication of the system and control. Also, to regulate terminal voltage of DFIG-WT in steady state, static synchronous compensators (STATCOM) have been installed at the point of common coupling (PCC) as centralized voltage regulation solution [8-12]. The ability of the STATCOM to provide fast dynamic reactive power compensation resulted in enhancing the transient performance of wind power plant [11, 12]. However, the STATCOM is not used alone for the DFIG ride-through capability since it cannot protect the RSC during a grid fault. In other words, a crowbar circuit is added to rotor side to protect the RSC from the rotor over-current during the grid fault. Series voltage injection approach by using dynamic voltage restorers (DVR), has been applied for LVRT capabilities [13-16]. However, during grid faults, a great amount of LC filters is designed to reduce the switching harmonics and braking chopper is required to dissipate the full power from the DFIG which increase the cost.

This paper proposes two VSCs-based configuration and control strategy to provide LVRT capability for DFIG wind turbine system in compliance with the recent stringent grid code requirements. Simulation results for a 2 MW-DFIG wind turbine system are provided to verify the validity of the proposed control strategy.

2. SYSTEM MODELING

The configuration of the overall system is shown in Figure 1. It comprises two VSCs-based configuration which is connected in series and in parallel with the power. As shown in Figure 1, a series VSC is connected with the line, through a series transformer to provide series compensation, while the remaining VSC is connected to the grid through interfacing inductor to inject the reactive power during the fault conditions, according to the requirement of the grid codes.

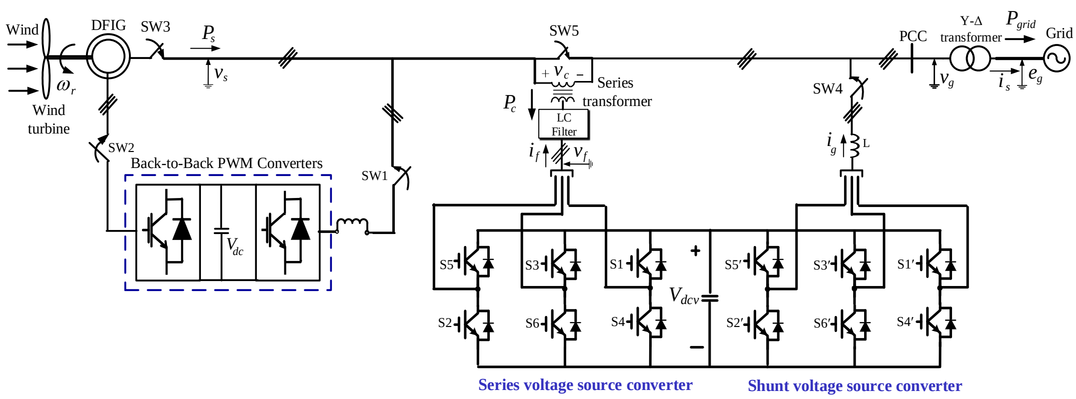

Figure 1. Circuit configuration of DFIG wind turbine systems with twoVSCs.

3. PROPOSED CONTROL SCHEME

When there is a dip in PCC voltage, the bypass switch (SW5) will open so that the series converter can establish injection voltage across the series transformer. Meanwhile, the shunt converter is activated to inject the reactive current according to the grid code requirement with priority.

3.1. Series voltage source converter

Figure 2 shows the block diagram of the voltage controller. The proposed algorithm is implemented in the *dq* reference frame, and it incorporates positive and negative-sequence voltage controllers. The negative-sequence controller is added to handle unbalanced voltage sags since the positive-sequence one can compensate only for balanced voltage dips. The positive sequence controller equations are given as [17, 18]

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

where the subscript "+" denotes the positive-sequence components of the voltage or the current. V_{cd}^{+} and V_{cq}^{+} are the *dq*-components of the voltage across the filter capacitor of the series VSC. V_{fd}^{+} and V_{fq}^{+} are the *dq*-components of the inverter output voltage of the series VSC. I_{sd}^{+} and I_{sq}^{+} are the *dq*-components of the grid current. I_{fd}^{+} and I_{fq}^{+} are the *dq*-components of the filter inductor current of the series VSC.

Since the negative sequence rotates in a direction opposite to the positive sequence, the cross-coupling terms between the *d*- and the *q*-components have opposite signs in the negative sequence controller. Hence, the negative sequence controller is given as [17, 18]

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

where the subscript "-" denotes the negative sequence component. V_{cd}^{-} and V_{cq}^{-} are the *dq*-components of the voltage across the filter capacitor of the series VSC. V_{fd}^{-} and V_{fq}^{-} are the *dq*-components of the inverter output voltage of the series VSC. I_{sd}^{-} and I_{sq}^{-} are the *dq* components of the grid current. I_{fd}^{-} and I_{fq}^{-} are the *dq*-components of the filter inductor current of the series VSC.

Based on (1) and (2), the voltage reference can be derived in a synchronous PI decoupling control strategy as

$$\begin{aligned} V_{fdq}^{+*} &= \left(K_p + K_i/s\right) e_p \\ V_{fdq}^{-*} &= \left(K_p + K_i/s\right) e_n \end{aligned} \tag{3}$$

where $V_{fdq}^{+*} = \begin{bmatrix} V_{fq}^{+*} \\ V_{fd}^{+*} \end{bmatrix}$, $V_{fdq}^{-*} = \begin{bmatrix} V_{fq}^{-*} \\ V_{fd}^{-*} \end{bmatrix}$, $e_p = \begin{bmatrix} V_{cq}^{+*} - V_{cq}^{+} \\ V_{cd}^{+*} - V_{cd}^{+} \end{bmatrix}$, $e_n = \begin{bmatrix} V_{cq}^{-*} - V_{cq}^{-} \\ V_{cd}^{-*} - V_{cd}^{-} \end{bmatrix}$

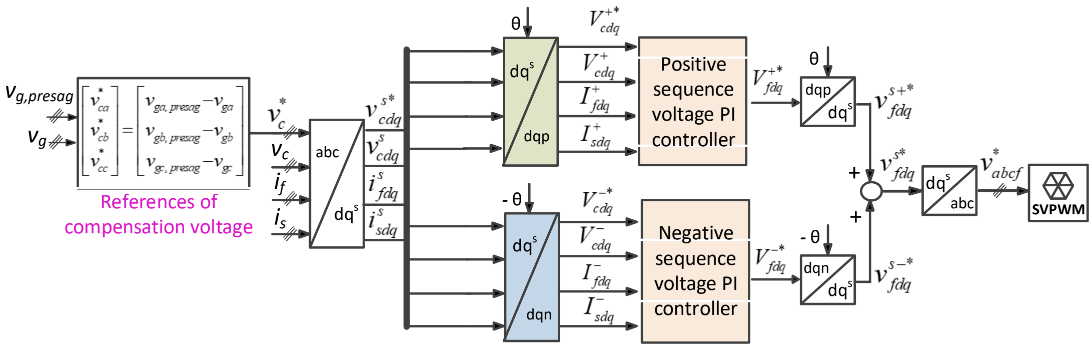

Figure 2. Control block diagram of a series VSC.

The block diagram of the proposed control scheme is shown in Figure 2, in which the components of the positive and negative sequence voltages in the dq-axis are separately regulated by using PI controller. Then, the outputs of the voltage controllers (V_{fdq}^{+*}, V_{fdq}^{-*}) are transformed to the voltage references in the abc reference frame (v_{abcf}^{*}), which are employed for the space vector pulse-width modulation (SVPWM).

3.2. Shunt voltage source converter

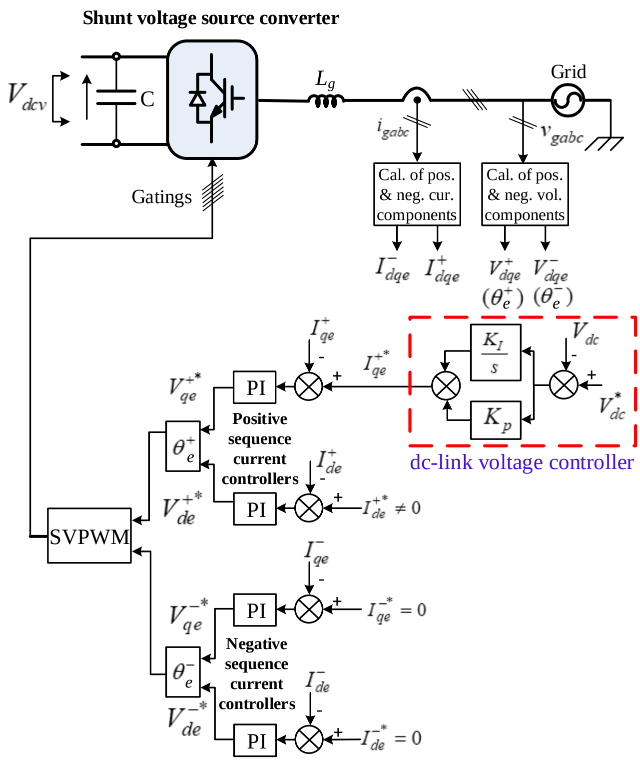

Figure 3. Control block diagram of a shunt VSC.

Shunt VSC is used to control the DC-link voltage and regulate the PCC voltage or inject the reactive current according to the grid code requirement [19]. Figure 3 shows the control block diagram of the shunt VSC, in which the components of the positive and negative sequence currents in the dq-axis are regulated, based on the PI controller. The reference of the positive sequence current component in q-axis (I_{qe}^{+*}) achieved from the output of the DC-link voltage controller [12], which allows controlling the active power exchange between the shunt converter and the electric grid. Meanwhile, the positive-sequence component of the d-axis current reference or the grid reactive current (I_{de}^{+*}) is selected to support the grid voltage recovery. The dq-axis current references of negative-sequence components (I_{dq}^{-*}) are set to zero to eliminate the unbalanced current components flowing into the grid. Then, the outputs of the current controllers are transformed to the three-phase abc reference frame, applied for SVPWM.

4. SIMULATION RESULTS

PSCAD simulation has been performed out to verify the feasibility of the proposed method for a 2 MW-DFIG wind turbine system. For the wind turbine: R = 44 m; ρ = 1.225 kg/m^3; λ_{opt} = 8; and the wind speed is constant at 11 m/s. 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 two VSCs: the DC-link capacitor is 8200 μF; the output LC filter of the series VSC is 0.2 mH and 8200 μF; the input L filter of the shunt VSC is 0.25 mH.

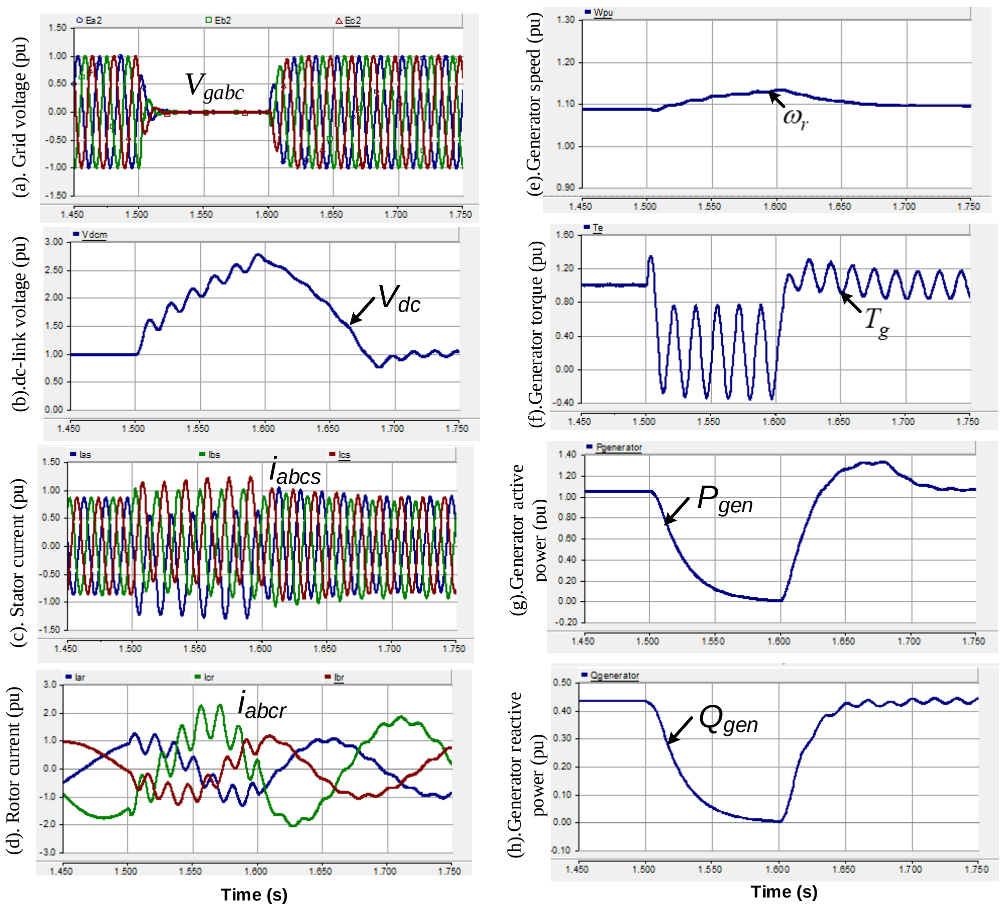

Figure 4. Performance of DFIG wind turbine system for the three-phase voltage interruption (in pu).

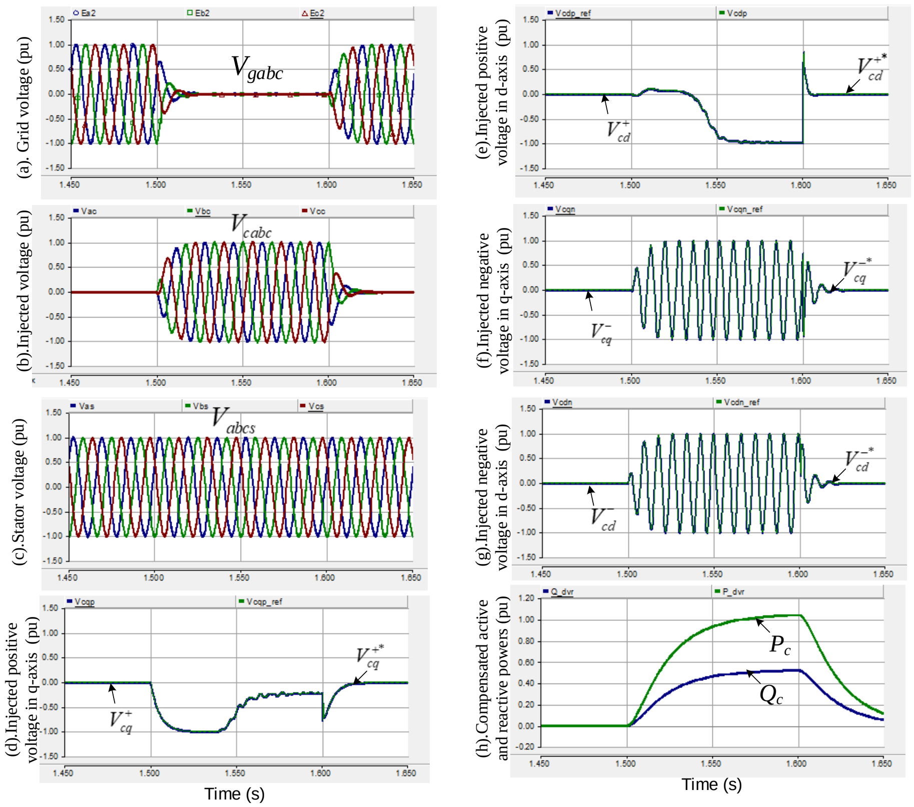

Figure 5. Performance of series VSC for the three-phase voltage interruption (in pu).

Figure 4 shows the system performance for three-phase voltage interruption without compensation, where the wind speed is assumed to be constant (16.5 m/s) for easy examination. The fault condition is three-phase voltage interruption for 0.1 s which is between 1.5 s and 1.6 s. Since the fault type is a balanced one, the negative-sequence component of the grid voltage does not exist. Due to the grid fault as shown in Figure 4(a), the DC-link voltage (see Figure 4(b)) of the DFIG converter without compensation reaches 2.8 pu, which is high enough to damage the dc capacitor and the converter switches. Also, the stator and rotor currents, which are shown from Figure 4(c) to 4(d), respectively, are much increased. Even the rotor currents in the case of the grid fault increase more than double, compared with the rated ones. In this case, the generator speed in Figure 4(e) accelerates to obtain the optimal value for the maximum power point tracking. However, due to the three-phase voltage interruption of the grid and the current limitation of the converters, the active and reactive generator powers are still decreased to zero without compensation are illustrated in Figure 4(g) and (h), respectively. Likewise, the generator torque which are illustrated in Figure 4(f), is also reduced with high oscillations during the grid voltage fault.

Figure 5 shows the performance of series VSC for three-phase voltage interruption. When the fault occurs as illustrated in Figure 5(a), the compensation voltages in Figure 5(b) are injected by the series VSC. With this compensation, the stator voltages in Figure 5(c) are still sinusoidal and kept at the rated value. The dq-axis positive sequence voltages of the series VSC are clearly seen from Figure 5(d) and (e), respectively. Figure 5(f) and (g) show the negative-sequence components of the grid voltage in dq-axis. With compensation, the injected active and reactive powers are produced from the series VSC, as illustrated in Figure 5(h).

Figure 6 shows the performance of shunt VSC for three-phase voltage interruption. When there is the fault as shown in Figure 6(a), the DC-voltage is regulated to be constant (see Figure 6(b)). Figure 6(c) shows the postitive current in q-axis. The reactive current is controlled to inject for the grid voltage recovery, which is selected, depending on the grid code requirement. In this case, the reactive current is selected to be 0.3 pu, as illustrated in Figure 6(d).

By applying both VSCs (series VSC and shunt VSC), the grid voltage is fully compensated for the three-phase interruption condition.

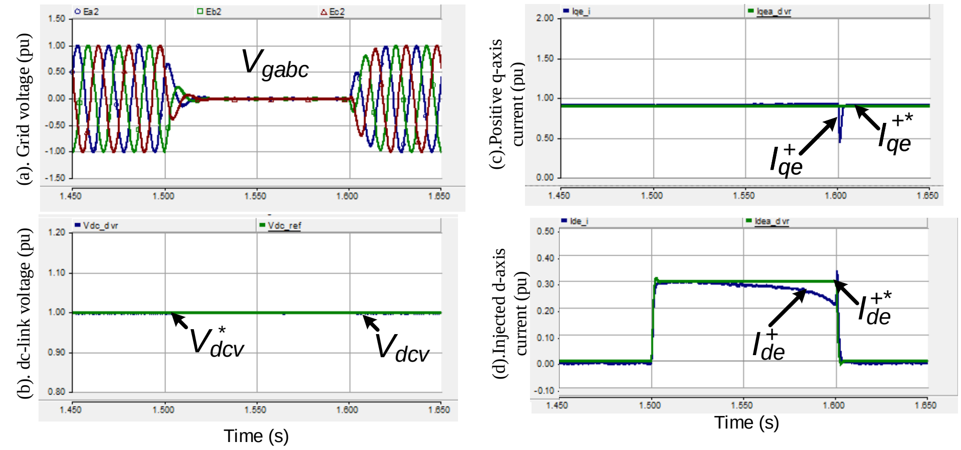

Figure 6. Performance of shunt VSC for the three-phase voltage interruption (in pu).

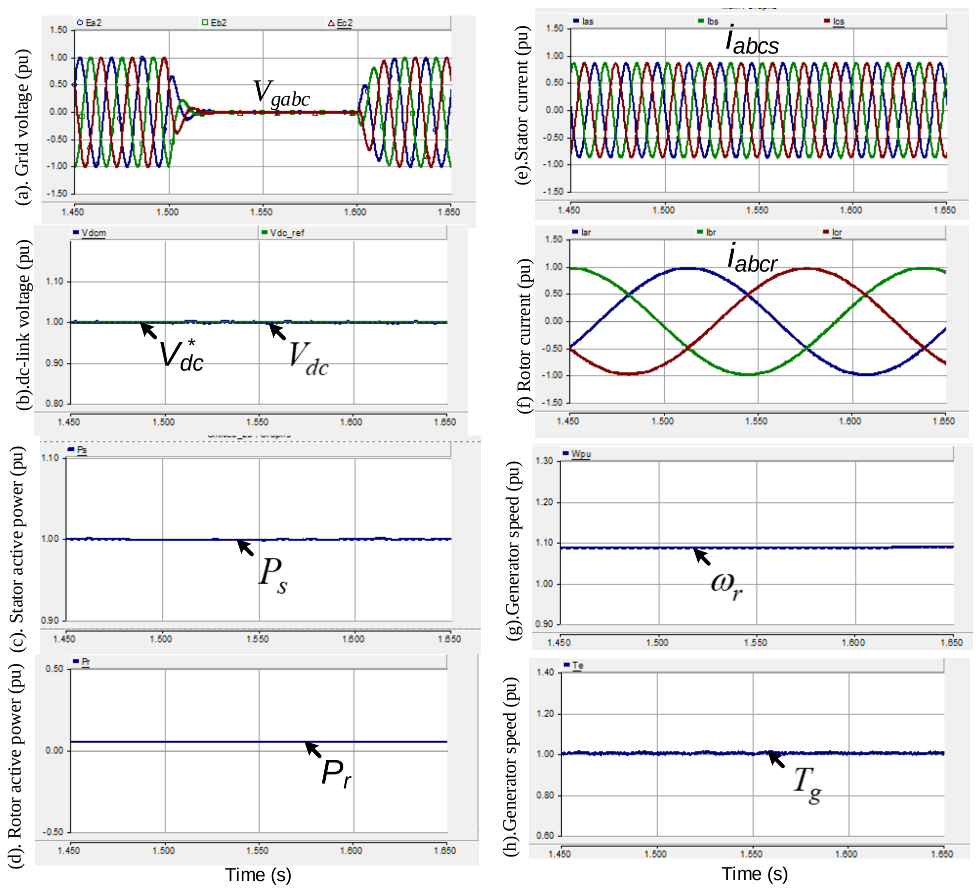

Figure 7. Performance of DFIG wind turbine system for three-phase voltage interruption (in pu).

Figure 7 shows the performance of DFIG wind turbine system for the three-phase voltage interruption. It is obvious from Figure 7 that due to the coordinated control scheme for both VSCs, all quantities of the DFIG at the grid faults can be kept the same as those without grid faults since the DFIG operation is not influenced by the grid faults. Therefore, the proposed method achieves the good operation for the DFIG wind turbine system under all types of the grid faults.

5. CONCLUSION

This paper has proposed the LVRT technique for a doubly fed induction generator DFIG-WT system under grid voltage fault conditions. With the proposed scheme, both shunt and series VSCs applied, enable to compensate the grid voltage simultaneously during the grid faults. The simulation results for 2 MW-DFIG wind turbine system using the proposed method at the grid faults gives as good performance as those without grid faults.

REFERENCES

1. Flannery P. S., Venkataramanan G. - A fault tolerant doubly fed induction generator wind turbine using a parallel grid side rectifier and series grid side converter, IEEE Transactions on Power Electronics **23** (3) (2008) 1126-1135.
2. Lei Y., Mullane A., Lightbody G., Yacamini R. - Modeling of the wind turbine with a doubly fed induction generator for grid integration studies, IEEE Transactions on Energy Conversion **21** (1) (2006) 257-264.
3. Akhmatov V. - Analysis of dynamic behavior of electric power systems with large amount of wind power, Ph.D. dissertation, Department of Electrical Power Engineering, Technical University of Denmark, Kongens Lyngby, Denmark (2003).
4. Lima F. K. A., Luna A., Rodriguez P., Watanabe E. H., Blaabjerg F. - Rotor voltage dynamics in the doubly fed induction generator during grid faults, IEEE Transactions on Power Electronics **25** (1) (2010) 118-130.
5. Meegahapola L. G., Littler T., Flynn D. - Decoupled-DFIG fault ride-through strategy for enhanced stability performance during grid faults, IEEE Transactions Sustainable Energy **1** (3) (2010) 2178-2192.
6. Sava G. N., Costinas S., Golovanov N., Leva S., Quan D. M. - Comparison of active crowbar protection schemes for DFIGs wind turbine, Proceedings of the 16th International Conference on Harmonics and Quality of Power (2014) 669-673.
7. Haidar A. M. A., Muttaqi K. M., Hagh M. T. - A coordinated control approach for DC link and rotor crowbars to improve fault ride-through of DFIG based wind turbines, IEEE Transactions Industry Applications **53** (4) (2017) 4073-4086.
8. Song Q., Liu W. - Control of a cascade STATCOM with star configuration under unbalanced conditions, IEEE Transactions on Power Electronics **24** (1) (2009) 45-58.
9. Zhang W. H., Lee S.-J., Choi M.-S. - Setting considerations of distance relay for transmission line with STATCOM, Journal of Electrical Engineering & Technology **5** (4) (2010) 522-529.
10. Pirouzy H. M., Bina M. T. - Modular multilevel converter based STATCOM topology suitable for medium-voltage unbalanced systems, Journal of Power Electronics **10** (5) (2010) 572-578.
11. Molinas M., Suul J., Undeland T. - Low voltage ride through of wind farms with cage generators: Statcom versus svc, IEEE Transaction on Power Electronics **23 (**3) (2008) 1104-1117.

12. Zou Y., Elbuluk M., Sozer Y. - Simulation comparisons and implementation of induction generator wind power systems, IEEE Transactions Industry Application **49** (3) (2013) 1119-1128.
13. Leon A., Farias M., Battaiotto P., Solsona J., Valla M. - Control strategy of a DVR to improve stability in wind farms using squirrel-cage induction generators, IEEE Transactions on Power System **26 (**3) (2011) 1609-1617.
14. Ramirez D., Martinez S., Platero C., Blazquez F., de Castro R. - Low-voltage ride-through capability for wind generators based on dynamic voltage restorers, IEEE Transactions on Energy Conversion **26** (1) (2011) 195-203.
15. El Moursi M., Goweily K., Kirtley J., and Abdel-Rahman M. - Application of series voltage boosting schemes for enhanced fault ride-through performance of fixed speed wind turbines, IEEE Transactions Power Delivery **29** (1) (2014) 61-71.
16. Wessels C., Gebhardt F., and Fuchs F. - Fault ride-through of a DFIG wind turbine using a dynamic voltage restorer during symmetrical and asymmetrical grid faults, IEEE Transactions on Power Electronics **26** (3) (2011) 807-815.
17. Ibrahim A. O., Nguyen T. H., Lee D.-C., Kim S.-C. - A fault ridethrough technique of DFIG wind turbine systems using dynamic voltage restorers, IEEE Transactions on Energy Conversion **26** (3) (2011) 871-882.
18. Van T. L., Nguyen N. M. D., Toi L. T., Trang T. T. - Advanced control strategy of dynamic voltage restorers for distribution system using sliding mode control input-ouput feedback linearization, Lecture Notes in Electrical Engineering **465** (2017) 521-531.
19. Van T. L. and Ho V. C. - Enhanced fault ride-through capability of DFIG wind turbine systems considering grid-side converter as STATCOM, Lecture Notes in Electrical Engineering **371** (2015) 185-196.

TÓM TẮT

KỸ THUẬT LƯỚT QUA ĐIỆN ÁP THẤP CHO HỆ THỐNG TUA-BIN GIÓ DÙNG MÁY PHÁT DFIG

Văn Tấn Lượng*, Nguyễn Phú Công
Trường Đại học Công nghiệp Thực phẩm TP.HCM
*Email: *luongvt@hufi.edu.vn*

Bài báo này đề xuất một kỹ thuật lướt qua điện áp thấp (LVRT) cho một hệ thống tua-bin gió dùng máy phát không đồng bộ nguồn kép (DFIG). Với phương pháp đề xuất, cả bộ chuyển đổi nguồn điện áp mắc nối tiếp và mắc song song được sử dụng, cho phép bù đồng thời đáp ứng điện áp của hệ thống trong trường hợp sự cố lưới điện. Đối với bộ chuyển đổi nguồn điện áp mắc nối tiếp (VSC), thuật toán điều khiển bao gồm bộ điều khiển điện áp kép được thực hiện cho hai thành phần thứ tự thuận và nghịch trong hệ tọa độ quay dq. Đối với bộ VSC mắc song song, thuật toán điều khiển bao gồm vòng lặp điều khiển dòng điện bên trong và vòng lặp điều khiển điện áp DC-link bên ngoài, trong đó vòng lặp điều khiển dòng điện được thực hiện trong hệ tọa độ quay dq. Kết quả mô phỏng đối với hệ thống tua-bin gió dùng máy phát DFIG công suất 2 MW đã chứng tỏ rằng phương pháp đề xuất cho kết quả vận hành tốt như trong trường hợp không có sự cố điện áp lưới.

Từ khóa: Máy phát không đồng bộ nguồn kép, sự cố lưới, lướt qua điện áp thấp, thành phần thứ tự thuận và nghịch, tua-bin gió.