CONTROL OF VOLTAGE COMPENSATION TO ENHANCE RIDE-THROUGH OF DFIG WIND TURBINE DURING SYMMETRICAL AND ASYMMETRICAL GRID FAULTS

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ABSTRACT

In this paper, the application of a series grid-side converter (SEGSC) connected to a wind-turbine-driven doubly fed induction generator (DFIG) is introduced. The setup allows the wind turbine system an uninterruptible fault ride-through of voltage dips. The SEGSC can compensate the faulty line voltage, while the DFIG wind turbine can continue its nominal operation as demanded in actual grid codes. The simulation results for the 2 MW-DFIG wind turbine system with the SEGSC compensation are presented, especially for asymmetrical grid faults, gives as good performance as those without grid faults.

Keywords: Doubly-fed induction generator, low-voltage ride-through, series compensation, voltage sag, wind turbine.

1. INTRODUCTION

A doubly fed induction generator (DFIG) is a common subsystem for large variable speed wind turbines that are connected to a and wherein, the stator windings are directly connected to the point of common coupling (PCC) via a transmission transformer. The rotor windings are controlled by a back-to-back converter that serves as a power interface between the rotor windings and the PCC. The power rating of the back-to-back converter mainly depends on the speed operation range of the DFIG, typically designed as 30% of nominal rating of the wind turbine. Thus, severe voltage sags and the resulting stator flux place a significant electrical stress on the machine-side converter and thereby increase mechanical stress on the gearbox as well [1, 2].

During deep balanced voltage sags, high per-unit currents and shaft torque pulsations are known to appear in the standard DFIG wind turbine architecture [3, 4]. In the literature, several solutions have been proposed to improve ride-through capability of DFIG [5-11]. A series braking resistance applied to the stator windings during a voltage sag has been shown to be able to reduce torque and current spikes in the DFIG [5]. Either a silicon controlled rectifier rotor crowbar circuit or a three-phase rectifier and adjustable resistive load have been introduced to improve the rotor circuit, from which have demonstrated enhancement in the DFIG ride-through capability [6-9]. However, as penetration of wind power into electric grid gets larger, much more stringent grid codes are being set up [12]. According to the recent regulations, wind turbines are not only required to stay connected to ride through the grid faults, but also are required to inject reactive current for assisting the grid to recover to its rated voltage. The braking resistor and the crowbar technology do not fulfill the grid codes, as the turbine cannot supply reactive power during the duration of the activation of the braking resistor or the crowbar. In order to satisfy the grid codes, static synchronous compensator (STATCOM) and dynamic voltage restorer (DVR) to enhance the ride-through capability of wind turbines or wind farms [13-15]. STATCOM is connected in parallel to the line, referred as shunt voltage compensation while DVR is connected in series with the line via the transformer, referred as series voltage compensation. However, STATCOM is still challenging to cope with severe voltage fault since it is based on shunt compensation. Compared with a parallel reactive power/voltage compensator, a series compensator would be much more effective in restoring voltage in strong grid utility, if steps are taken to minimize the power capacity of the devices.

In this paper, the application of a SEGSC that is connected to a wind-turbine-driven DFIG to allow uninterruptible fault ride-through of voltage dips fulfilling the grid code requirements is investigated. The SEGSC can compensate the faulty line voltage, while the DFIG wind turbine can continue its nominal operation as demanded in actual grid codes. Simulation results for a 2 MW-DFIG wind turbine system are provided, especially for asymmetrical grid faults, gives as good performance as those without grid faults.

2. SYSTEM MODELING

A single-line schematic of the DFIG with SEGSC is shown in Figure 1. As in a conventional DFIG, the rotor windings of the machine are accessed via slip rings and connected to a three-phase converter referred to as MSC. The MSC shares a dc bus with a second converter connected in parallel with the grid and DFIG stator, referred to as the shunt grid-side converter (SHGSC). The shared dc link enables power to flow between the rotor circuit of the DFIG and the grid connection. The proposed topology includes an additional converter connected in series with the stator windings of the DFIG, referred to as series GSC.

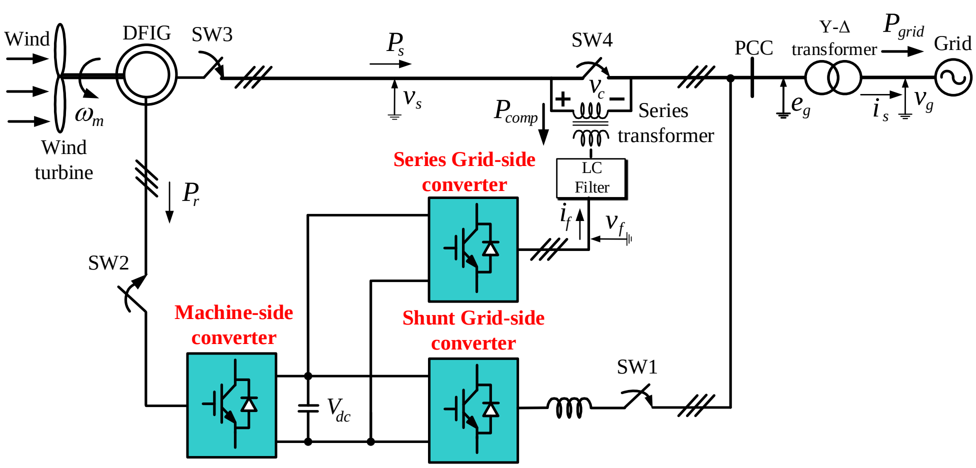

Figure 1. DFIG wind turbine system with SEGSC.

The modeling of the SEGSC is briefly described in this section, in which the components of the currents and voltages of the SEGSC can be expressed in synchronous d-q reference frame as follows [15, 16]

$$\begin{cases} \dot{V}_{cdq} = \dfrac{1}{C_f} I_{fdq} - \dfrac{1}{C_f} I_{sdq} - j\omega_e V_{cdq} \\ \dot{I}_{fdq} = \dfrac{1}{L_f} V_{fdq} - \dfrac{1}{L_f} V_{cdq} - j\omega_e I_{fdq} \end{cases} \tag{1}$$

where L_f is the filter inductance, C_f is the filter capacitance, V_{fdq} is the *dq*-components of the inverter output voltage of the SEGSC, V_{cdq} is the *dq*-components of the voltage across the filter capacitor of the SEGSC, I_{fdq} is the dq axis filter inductor currents of the SEGSC, I_{sdq} is the *dq*- components of the grid current, and ω_e is the source angle frequency.

3. SEGSC CONTROL

3.1. Compensation of voltage sag

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

$$\begin{bmatrix} v^*_{comp,a} \\ v^*_{comp,b} \\ v^*_{comp,c} \end{bmatrix} = \begin{bmatrix} v_{ga,presag} - v_{ga} \\ v_{gb,presag} - v_{gb} \\ v_{gc,presag} - v_{gc} \end{bmatrix} \tag{2}$$

where $v_{ga,presag}$, $v_{gb,presag}$ and $v_{gc,presag}$ 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. Voltage control of SEGSC

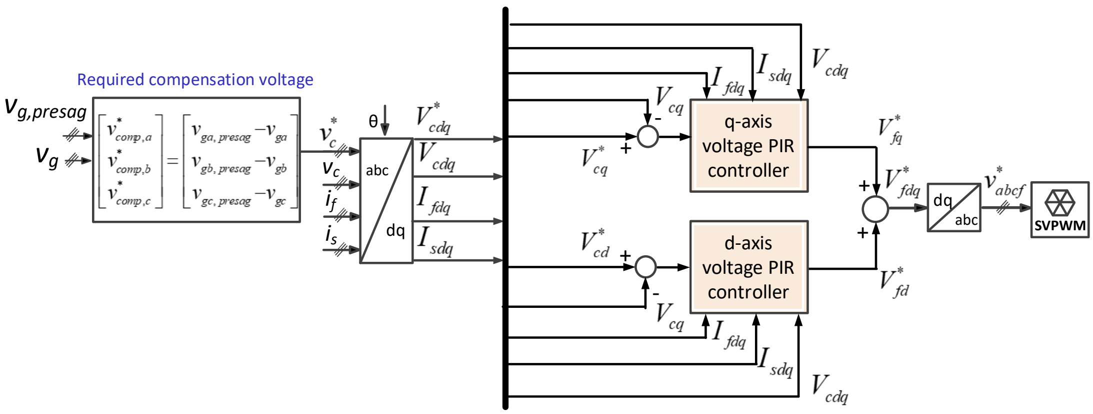

Figure 2. Voltage control block diagram of SEGSC.

A modified double vector control algorithm was presented in [17]. This algorithm is implemented in the *dq* reference frame and consists of an inner current control loop and an outer voltage control loop, respectively. However, it is noted that it is impossible to use inductor current control of the SEGSC for the DFIG because the inductor current that flows through the series transformer of the SEGSC is also the DFIG output current that is used to regulate the DFIG output power. A conflict will appear if this series transformer current is used to control the SEGSC output voltages.

The proposed algorithm is implemented in the *dq* reference frame. In the case of unbalanced dips, the *d* and *q* components in the controller are not dc quantities and thus using only the proportional-integral (PI) controller is not proper. Thus, the voltage controllers based on proportional-integral and resonant (PIR) control that are controlling directly the voltage across the filter capacitors without inner current controllers are used here. The transfer function of the PIR voltage controller is defined as

$$G_{PIR}(s) = K_p + \frac{K_i}{s} + \frac{K_{re}s}{s^2 + (2\omega_e)^2} \tag{3}$$

Here K_p, K_i and K_{re} are the proportional, integral and resonant gains of the controller, in which K_p and K_i are calculated in terms of the filter parameters and the sampling time; $K_p = C_f / (10T_s)$ and $K_i = K_p / (10T_s)^2$. T_s is the sampling time, which is selected to be 10^{-4}s [18].

Figure 3 describes the magnitude and phase characteristics of the open loop transfer functions for both the PI controller and the PIR one. Under the grid fault conditions, the voltage of the SEGSC may contain the DC and second-order oscillation component [15]. Thus, the proportional integral and resonant regulators are employed to eliminate the steady-state errors. In this work, K_{re} is selected to be 250 by using the trial and error method.

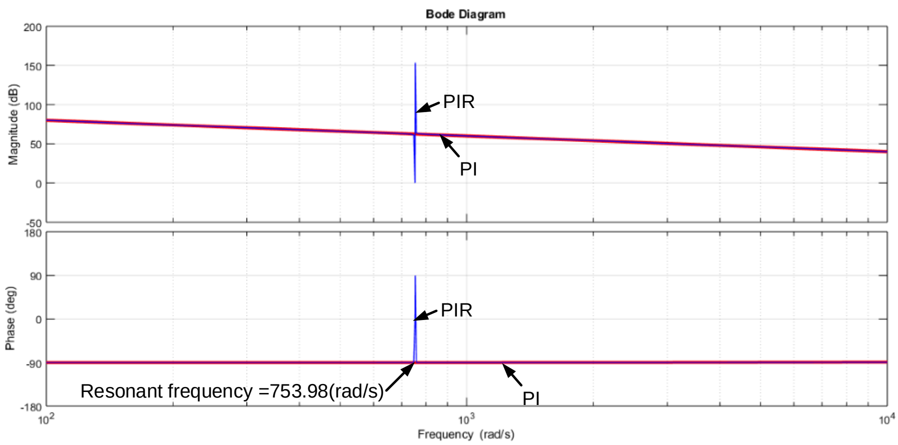

Figure 3. Bode diagram of open-loop PI and PIR controllers.

The block diagram of the voltage compensation controllers is shown in Figure 2, in which the dq-axis components of the voltages are separately regulated by using PIR controller. Then, the output of the control (V_{fdq}^*) is transformed to the voltage references in three-phase abc reference frame (v_{abcf}^*), employed for the space vector pulse-width modulation (SVPWM). The SVPWM method for the voltage vector (v_{abcf}^*) are applied to produce the switching pulses, which have been described in [29].

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. The parameters of the wind turbine, generator and series grid-side converter are listed in Table 1, 2 and 3, respectively.

Table 1. Parameters of wind turbine

Parameter	Value
Rated power	2 MW
Blade radius	45 m
Air density	1.225 kg/m^3
Max. power conv. coefficient	0.4
Cut-in speed	3 m/s
Cut-out speed	25 m/s
Rated wind speed	16.5 m/s
Blade inertia	6.3x10^6 kg.m^2

Table 2. Parameters of 2 MW- DFIG

Parameter	Value
Rated power	2 MW
Grid voltage	690 V
Stator voltage/frequency	690 V/60 Hz
Stator resistance	0.00488 pu
Rotor resistance	0.00549 pu
Stator leakage inductance	0.0924 pu
Rotor leakage inductance	0.0995 pu
Generator inertia	200 kg.m^2

Table 3. Parameters of SEGSC

Parameter	Value
Capacity	0.8 MW
DC-link capacitor	8200 μF
Inverter output filter	L=0.1 mH, C =1000 μF
Switching frequency	2.5 kHz
Series transformer	0.8 MW, 690 V/ 690 V

4.1. Symmetrical grid fault

Figure 4 shows the system performance for balanced grid voltage fault (symmetrical grid fault) without using SEGSC system, where the wind speed is assumed to be constant (16.5 m/s) for easy investigation. The fault condition is 50% sag in three phases for 0.1 s which is between 1.4 s and 1.5 s. When there is the grid balanced voltage sag (V_{gabc}) as shown in Figure 4(a), the negative-sequence component of the grid voltage does not exist. As can be seen from Figure 4 (b), the DC-link voltage (V_{dc}) of the DFIG converter without using SEGSC reaches 1.2 pu, which can damage the dc capacitor and the converter switches. Also, the stator and rotor currents (i_{abcs}, i_{abcr}), as illustrated in Figure 4(c) to 4(d), respectively, are increased. Especially, the rotor currents are twice higher than rated values (1pu). In this case, the generator speed (ω_r) which are illustrated in Figure 4(e) accelerates to achieve the optimal value for tracking the maximum power point. Similarly, the generator torque (T_g) in Figure 4(f) is also decreased under the grid voltage fault.

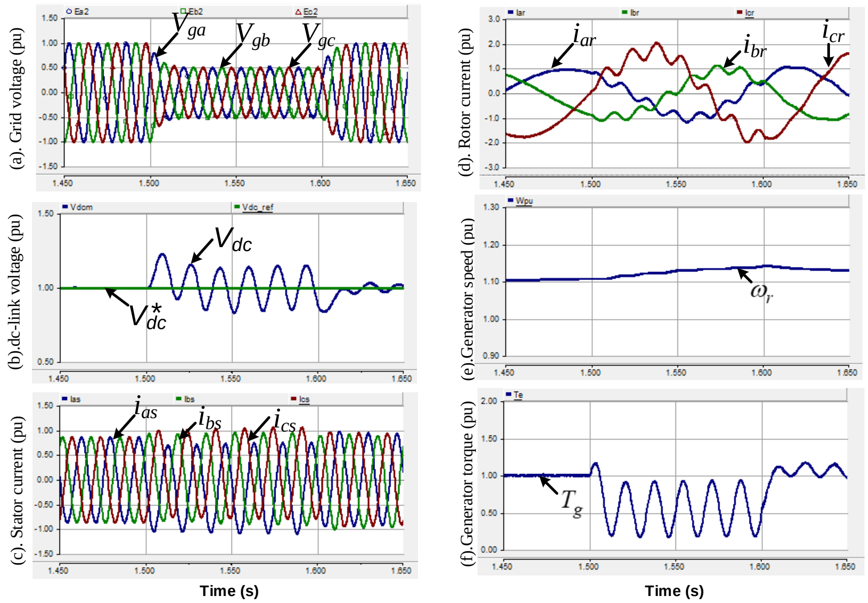

Figure 4. Performance of DFIG wind turbine system for balanced voltage sag (in pu).

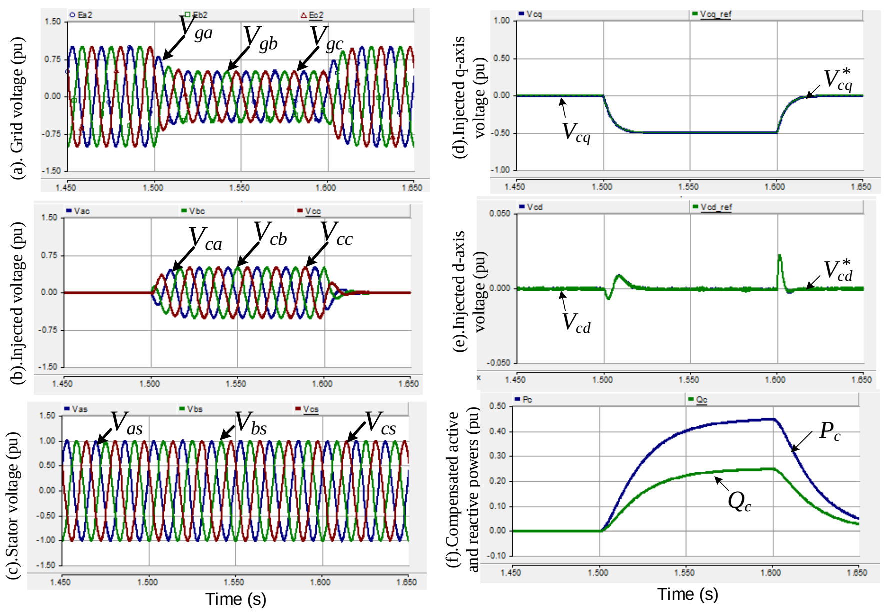

Figure 5. Performance of series grid-side converter system for balanced voltage sag (in pu).

Figure 5 shows the performance of SEGSC system under balanced grid voltage fault. Due to balanced voltage sag, as shown in Figure 5(a), the compensation voltages (V_{cabc}) in Figure 5(b) are injected by the SEGSC system. With the compensation, the stator voltages (V_{abcs}) in Figure 5(c) compensated, are kept at the rated value. The dq-axis voltages (V_{cdq}) of the SEGSC are seen from Figure 5(d) and (e), respectively. Aslo, the active and reactive powers (P_c , Q_c) injected by the SEGSC are shown in Figure 5(f). Without SEGSC for voltage compensation, the stator and rotor currents, and torque give high ripples, 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 in case of unbalanced voltage fault. It is obvious from Figure 6 that all quantities of the DFIG with the proposed SEGSC such as DC-link voltage, stator active and reactive powers, stator and rotor currents, generator speed and torque at grid faults have the same waveforms as those without grid faults. On the other hands, the DFIG still operates normally even though the grid fault occur. Thus, the proposed method obtains the good operation for the DFIG wind turbine system during symmetrical grid fault.

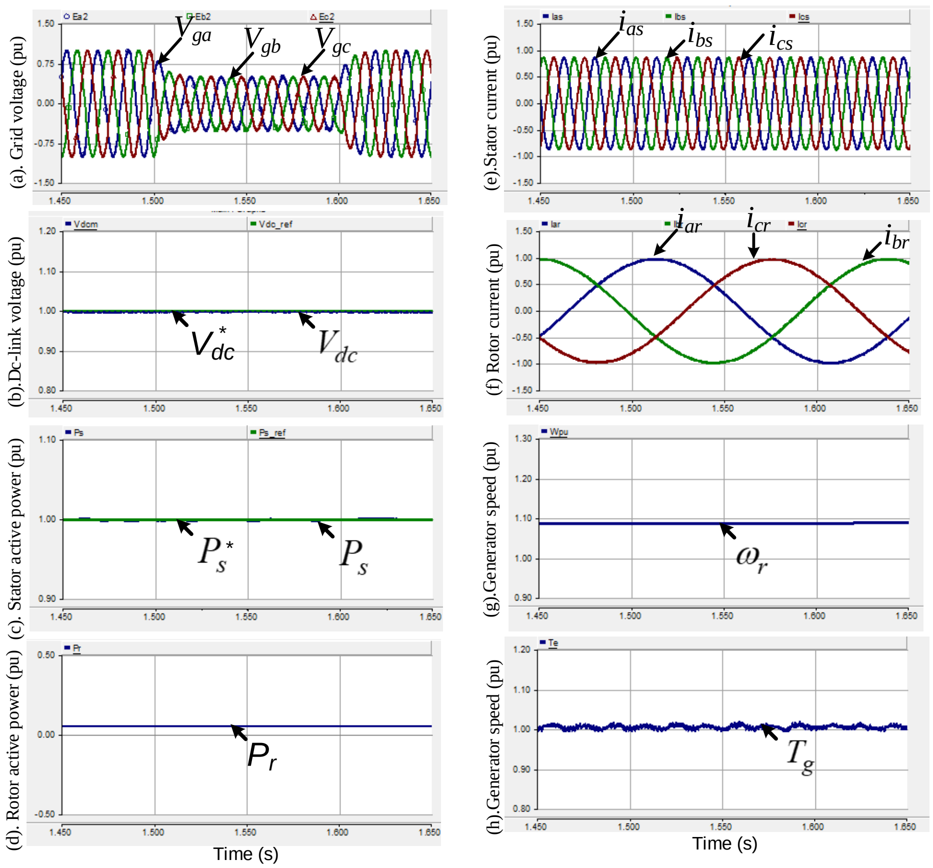

Figure 6. Performance of DFIG wind turbine system for balanced voltage sag (in pu).

4.2. Asymmetrical grid fault

Figure 7 shows the system performance for unbalanced grid voltage fault (asymmetrical grid fault) without using SEGSC system. The fault condition is 40% sag in both the grid A-phase and C-phase voltages for 0.1 s which is between 1.4 s and 1.5 s. Since the fault type is an unbalanced one, the negative-sequence components in dq-axis of the grid voltage appear. Due to the grid unbalanced voltage sag (V_{gabc}) as illustrated in Figure 7(a), the DC-link voltage (V_{dc}) (see Figure 7 (b)) of the DFIG converter without compensation reaches 3 pu, which is high enough to deteriorate the dc capacitor as well as the switches of the converter. In this case, the stator and rotor currents (i_{abcs}, i_{abcr}) which are seen in Figure 7(c) and (d), respectively, are much increased. The stator current is higher than the rated value (1 pu) and the rotor current reaches 2.6 pu. Also, the generator speed (ω_r) in Figure 7(e) is increased and the generator torque (T_g) in Figure 7(f) gives high oscillations.

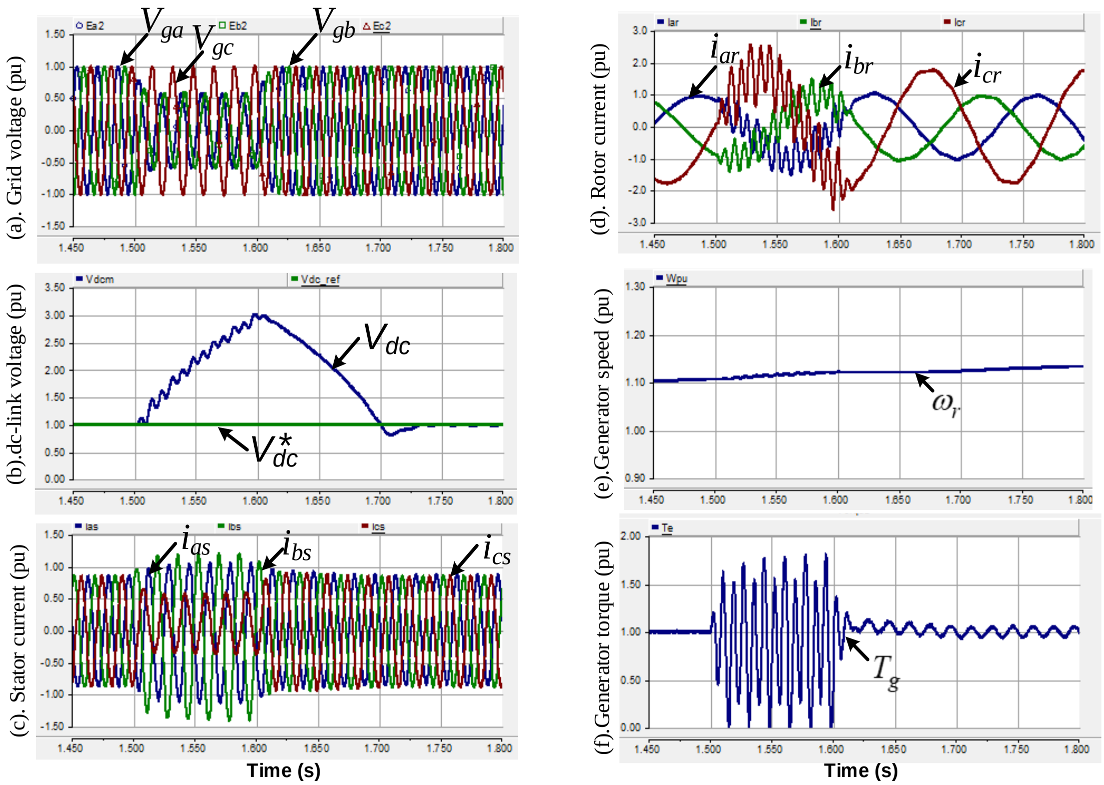

Figure 7. Performance of DFIG wind turbine system for unbalanced voltage sag (in pu)

Figure 8 shows the performance of SEGSC system under unbalanced grid voltage fault. When there is an unbalanced voltage sag in Figure 8(a), the SEGSC system injects the compensated voltages (V_{cabc}) into the grid, as shown in Figure 8(b). Thus, the stator voltages (V_{abcs}) in Figure 8(c) are kept at the rated value (1pu), as if it is in the normal grid condition. The components of the dq-axis voltage (V_{cdq}) of the SEGSC system are produced, as shown in Figure 8(d) and (e). Without compensation, the ripples of the stator and rotor currents (i_{abcs}, i_{abcr}), and generator torque (T_g), as illustrated from Figure 7(c) to 7(f), respectively are significantly increased. However, they are kept almost constant with the compensation scheme based on the SEGSC.

Figure 9 shows the performance of DFIG wind turbine system in case of unbalanced voltage fault. With the proposed SEGSC under grid faults, the DC-link voltage, stator active and reactive powers, stator and rotor currents, generator speed and torque can be kept the same as those in the normal grid condition. This means that the DFIG can work well, as if it does without the grid faults. Thus, the proposed method gives the good operation for the DFIG wind turbine system during asymmetrical grid fault.

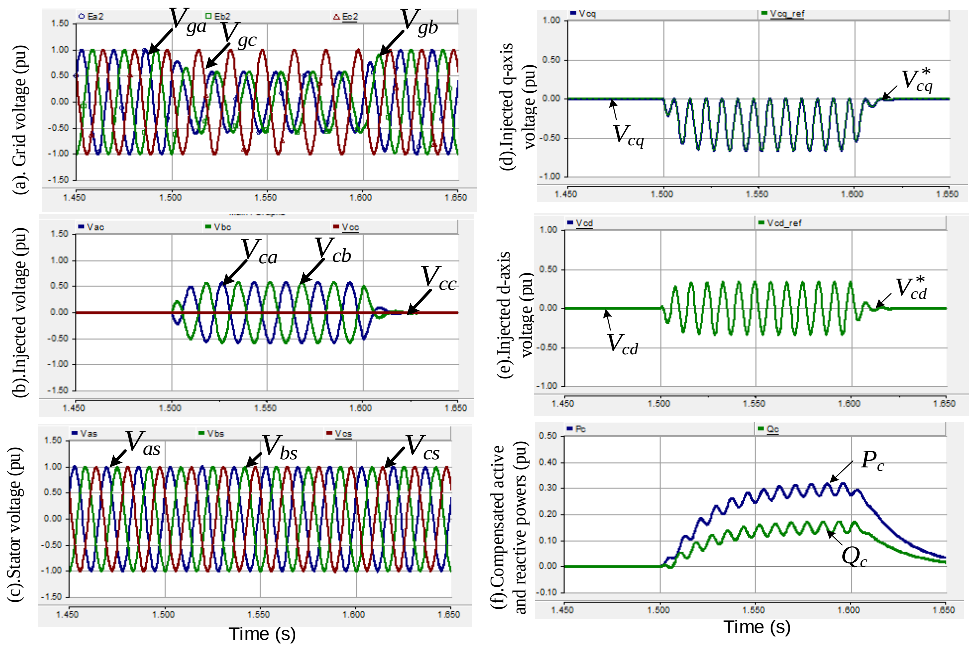

Figure 8. Performance of series grid-side converter system for unbalanced voltage sag (in pu)

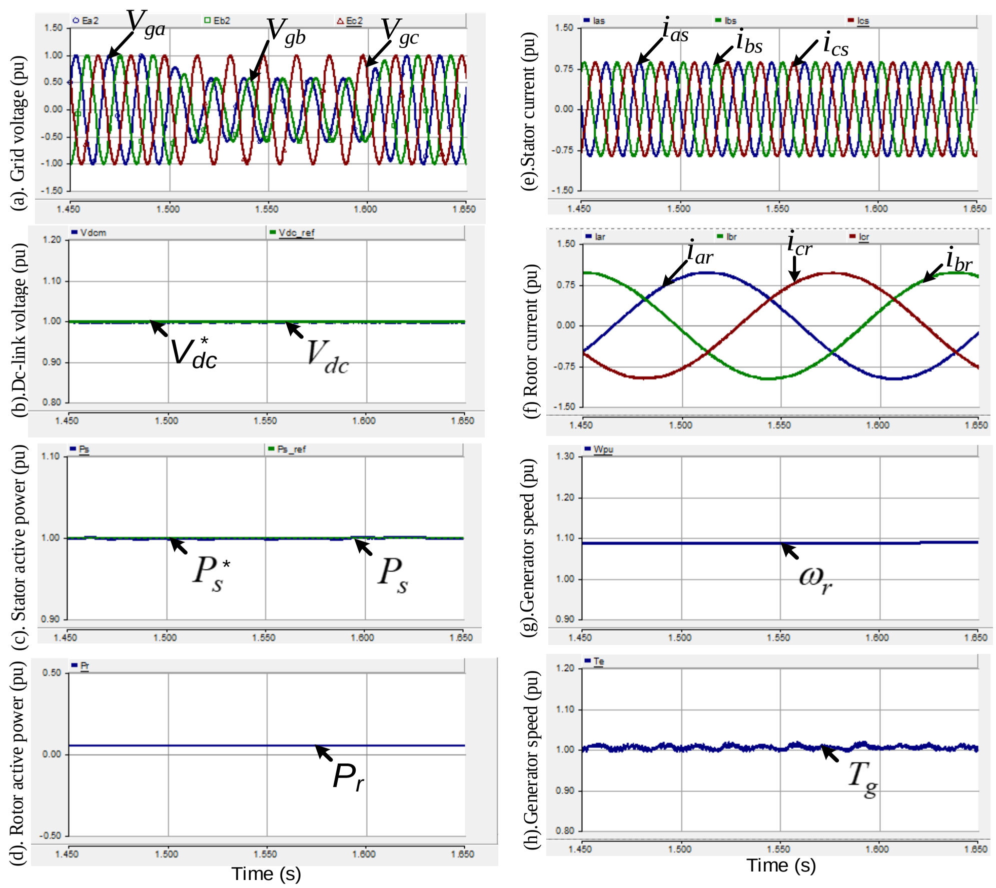

Figure 9. Performance of DFIG wind turbine system for unbalanced voltage sag (in pu).

5. CONCLUSION

The application of a SEGSC connected to a wind-turbine-driven DFIG to allow uninterruptible fault ride through of grid voltage faults is introduced. The SEGSC can compensate the faulty line voltage, while the DFIG wind turbine can continue its nominal operation. Simulation results for a 2 MW wind turbine under asymmetrical two-phase grid fault and symmetrical three-phase fault show the effectiveness of the proposed technique.

REFERENCES

1. Anaya-Lara O., Wu X., Cartwright P., Ekanayake J. B., and Jenkins N. - Performance of doubly fed induction generator (DFIG) during network faults, Wind Engineering **29** (1) (2005) 49-66.
2. Polinder H., van der Pijl F.F.A., de Vilder G.J., Tavner P.J. - Comparison of direct-drive and geared generator concepts for wind turbines, IEEE Transactions on Energy Conversion **21** (3) (2006) 725-733.
3. Morren J. and de Haan S. W. H. - Ridethrough of wind turbines with doubly-fed induction generator during a voltage dip, IEEE Transactions on Energy Conversion **20** (2) (2005) 435-441.
4. Dittrich A., Stoev A. - Comparison of fault ride-through for wind turbines with DFIM generators, in Proceedings 11th European Conference Power Electronics Applications (2005) 1-8.
5. Causebrook A., Atkinson D. J., Jack A. G. - Fault ride-through of large wind farms using series dynamic braking resistors (March 2007), IEEE Transactions on Power System **22** (3) (2007) 966-975.
6. Morren J. and de Haan S. W. H. - Ride-through of wind turbines with doubly-fed induction generator during a voltage dip, IEEE Transactions on Energy Conversion **20** (2) (2005) 435-441.
7. Gomis-Bellmunt O., Junyent-Ferre A., Sumper A., Bergas-Jan J. - Ride-through control of a doubly fed induction generator under unbalanced voltage sags, IEEE Transactions on Energy Conversion **23** (4) (2008) 1036-1045.
8. Peng L., Francois B., Li Y. - Improved crowbar control strategy of DFIG based wind turbines for grid fault ride-through, in Proceedings IEEE 24th Annual Applied on Power Electronics Conference and Exposition (2009) 1932-1938.
9. Zhou P. and He Y. - Control strategy of an active crowbar for DFIG based wind turbine under grid voltage dips, in Proceedings International Conference on Electrical Machines and Systems (2007) 259-264.
10. 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.
11. Abdel-Baqi O., Nasiri A. - A dynamic LVRT solution for doubly-fed induction generators, IEEE Transactions on Power Electronics **25** (1) (2010) 193-196.
12. Luo J., Zhao H., Lu X., Gao S., Ma Q. , Terzija V. - A Review of low voltage ride through in DFIG under unbalanced grid faults, 2019 IEEE PES GTD Grand International Conference and Exposition Asia (GTD Asia) (2019) 718-723.

13. Nguyen T. H., Lee D. C., Van T. L., Kang J.-H. - Coordinated control of reactive power between STATCOMs and wind farms for PCC voltage regulation, Journal of Power Electronics **13** (5) (2013) 909-918.

14. 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.

15. 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.

16. 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.

17. Awad H., Svensson J., Bollen M. - Mitigation of unbalanced voltage dips using static series compensator, IEEE Transactions on Power Electronics **19** (3) (2004) 837-846.

18. Kim M.-B., Moon G.-W., Youn M.-J. - Synchronous PI decoupling control scheme for dynamic voltage restorer against a voltage sag in the power system, Proceedings of Annual IEEE Conference on Power Electronics Specialists **2** (2004) 1046–1051.

19. Kim J.-S. and Sul S.-K. - A novel voltage modulation technique of the space vector PWM, T. IEE Japan **116-D** (8) (1996) 820-825.

TÓM TẮT

ĐIỀU KHIỂN BỒI HOÀN ĐIỆN ÁP ĐỂ CẢI THIỆN KHẢ NĂNG LƯỚT QUA ĐIỆN ÁP THẤP CỦA TUA-BIN GIÓ DÙNG MÁY PHÁT DFIG TRONG TRƯỜNG HỢP SỰ CỐ LƯỚI ĐỐI XỨNG VÀ BẤT ĐỐI XỨNG

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Bài báo giới thiệu việc áp dụng bộ biến đổi nối tiếp phía lưới (SEGSC) được kết nối với tua-bin gió dùng máy phát không đồng bộ nguồn kép (DFIG). Việc thiết lập mô hình này cho phép hệ thống tua-bin gió lướt qua sự cố lưới khi có sụt áp sâu. SEGSC có thể bồi hoàn điện áp của đường dây sự cố, trong khi tua-bin gió dùng máy phát DFIG có thể tiếp tục hoạt động bình thường theo quy luật làm việc của lưới thực tế. Các kết quả mô phỏng đối với hệ thống tua-bin gió 2 MW-DFIG có sử dụng bộ bù SEGSC cho kết quả vận hành tốt như trường hợp không có sự cố, đặc biệt đối với sự cố lưới không đối xứng.

Từ khóa: Máy phát không đồng bộ nguồn kép, lướt qua điện áp thấp, bồi hoàn nối tiếp, độ võng điện áp lưới, tua-bin gió.