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# LOW-VOLTAGE RIDE-THROUGH CAPABILITY FOR DFIG WIND TURBINE SYSTEM USING CROWBAR AND BRAKING CHOPPER

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## ABSTRACT

This paper proposes a low-voltage ride-through (LVRT) capability for a doubly-fed induction generator (DFIG) wind turbine (WT) system. With the proposed method, a crowbar connected at the rotor-side of the DFIG and a braking chopper (BC) connected in paralell with DC-link capacitor of back-to-back converters have been applied. By this, the crowbar enables to well improve responses of system during the grid faults. Also, to protect the DC capacitor from its overvoltage, a braking chopper has been employed. The simulation for 2 MW-DFIG wind turbine system during the grid faults using PSCAD software has been performed to verify the effectiveness of the proposed method.

*Keywords:* Crowbar, braking chopper (BC), doubly-fed induction generator (DFIG), low-voltage ride-through (LVRT), grid fault, wind turbine (WT).

## 1. INTRODUCTION

A doubly fed induction generator (DFIG) is a common subsystem for large variable speed wind turbine (WT) whereas the stator windings are directly connected to the grid and the rotor windings are served as a power interface between the rotor windings and the grid through back-to-back pulse-width modulation (PWM) converter. One of the most important reasons is that the converter only has to handle a fraction (25% - 30%) of the total power which mainly relies on the speed operation range of the DFIG. Normally, the active and reactive powers can be independently controlled at the rotor-side converter (RSC), while the grid-side converter (GSC) controls the DC-link voltage, and provides the exchange of the reactive power to the electrical grid. However, the converter is quite sensitive to the grid disturbances, since the stator of the DFIG is directly connected to the grid, and the capacity of the converter is limited. Figure 1 depicts DFIG-based WT system connected to a 33 kV distribution network.

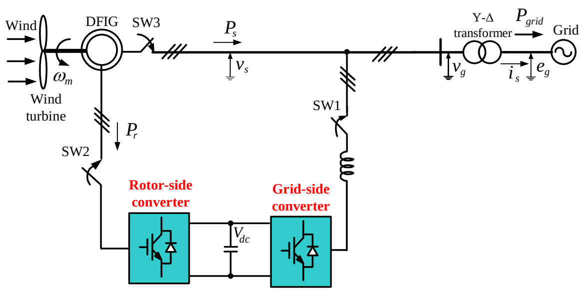


*Figure 1.* Circuit configuration of DFIG wind turbine systems

According to recent grid code as illustrated in Figure 2, new WT installations have to stay connected to the grid for voltage dips, which means that a new WT has to provide the ride- through capability during the voltage dips [1].

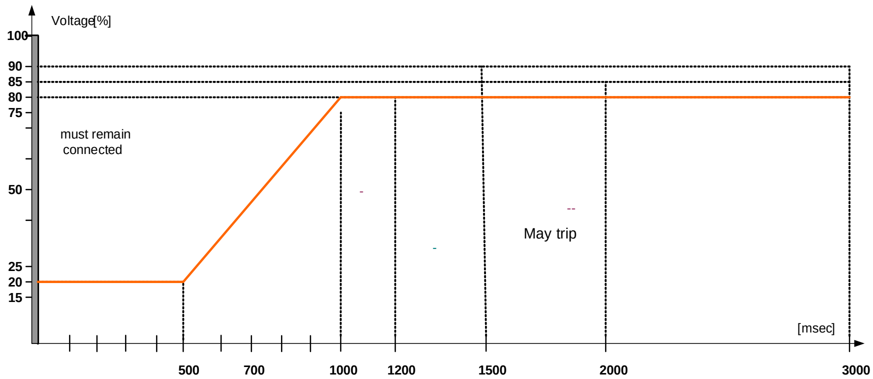


*Figure 2*. Grid code [1]

There are two groups of approaches which have been proposed for the LVRT capability enhancement of DFIGs. The first group of LVRT approaches uses external devices consisting of external passive and active equipments and other additional devices. Some LVRT methods apply external passive and active equipments such as crowbar, fault current limiter, and series damping resistor for LVRT improvement [2-5]. Firstly, a different comparison of the two DC crowbar has been made accomplish the LVRT requirements [2]. Next, the LVRT analysis is done among the series devices such as fault current limiter, and series damping resistor, etc. regarding to LVRT capability improvement of performances, implementation feasibility, and cost [3, 4]. Then, the superconducting current limiter (SCL) is considered to place in the the rotor side and in the DC-link [5]. Finally, other LVRT ones use supercapacitor energy storage system [6], magnetic energy storage device [7, 8], static compensation (STATCOM) [9, 10] and voltage-source converter connected in series between the stator and grid [11, 12]. Most of them may be technically feasible but are costly due to the requirement of additional converters and other equipment.

The second LVRT solutions using the modified control schemes and using advanced control methods. By using these modified control schemes, the auxiliary damping signals obtained by the feedback of the stator flux and rotor current are added to get its rotor current reference or perform heuristic control methods. Also, the control schemes such as RSC control, transient stator and rotor back-emf voltages applying linear quadratic regulator control, sliding mode control, and intelligent control techniques have been employed for some LVRT remedies of the DFIG [13-17]. However, the the DFIG control-based LVRT approaches can not provide adequate response under voltage dips [18].

To improve the fault handling capacity and protect the DFIG converter from high rotor current during grid faults, a crowbar is normally adopted in order to reduce the high rotor currents and rotor voltages [19]-[20]. After the fault is ended, the DC link voltage can be kept following its reference value by controlling again the GSC. However, the DC link voltage is likely to be oscillated during or in the period after the fault clearance.

In this paper, a coordination between crowbar and braking chopper that is connected to a DFIG wind turbine system to allow the fault ride-through capability of voltage dips to satisfy the the grid code requirements has been investigated. With the proposed method, a crowbar connected at the rotor-side of the DFIG, while braking chopper (BC) connected in paralell with DC-link capacitor of back-to-back converters. The simulation results for 2 MW-DFIG wind turbine system at the grid faults are presented, can give good performance during the grid faults.

## 2. DFIG WIND TURBINE SYSTEM WITH CROWBAR

Figure 3 shows the DFIG wind turbine system connected with crowbar, in which the crowbar resistance is connected to the rotor side through a diode rectifier.

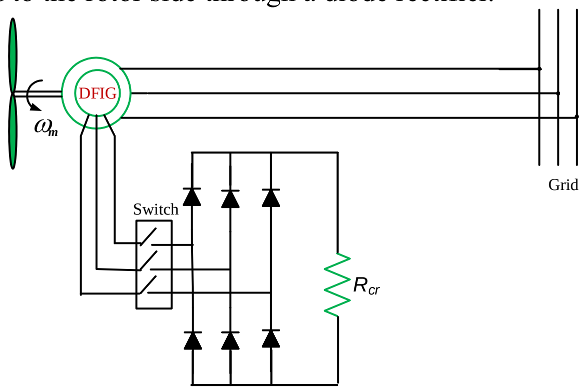


*Figure 3*. DFIG wind turbine system with crowbar.

Figure 4 shows the equivalent circuit of the DFIG without using crowbar. Assuming a three-phase symmetrical fault occurs in the grid at t = 0, and that the grid voltage drop depth of the wind turbine is *h*, there are [21]:

$$\vec{v}_s = \begin{cases} V_s \cdot e^{j(\omega_s - \omega_r)t} & \text{for } t < t_0 \\ (1-h)V_s \cdot e^{j(\omega_s - \omega_r)t} & \text{for } t \geq t_0 \end{cases} \quad (1)$$

where $V_s$ is a peak value of grid voltage before voltage dip and $\omega_s$ is grid angular frequency.

From Figure 3, the equivalent circuit of the DFIG with crowbar activated is shown in Figure 5.

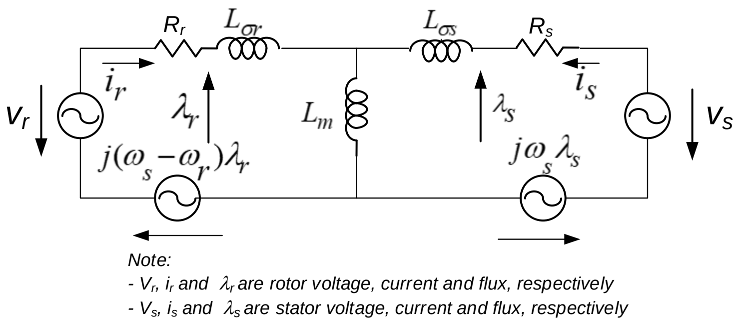


*Figure 4*. Equivalent circuit of the DFIG

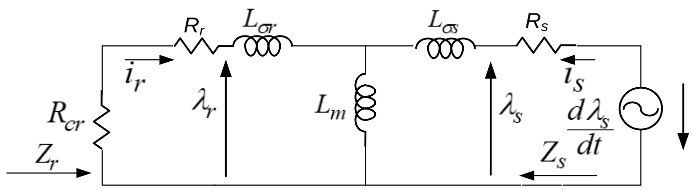

*Figure 5*. Equivalent circuit of the DFIG with crowbar

It is assumed that the crowbar resistance is much greater than stator and rotor resistances ($R_{cr} >> R_s, R_r$) and the magnetizing inductance is much greater than leakage stator and rotor inductances ( $L_m >> L_{\sigma s}, L_{\sigma r}$ ), the stator and rotor-side equivalent impedances are respectively written as

$$Z_s(s) = \frac{sL_s R_{cr} + s^2 L_m L_\sigma}{sL_r + R_{cr}} \quad (2)$$

$$Z_r(s) = sL_\sigma + R_{cr} \quad (3)$$

where $L_\sigma = L_{\sigma s} + L_{\sigma r}$, $L_s = L_{\sigma s} + L_m$, $L_r = L_{\sigma r} + L_m$.

Thus, the maximum transient currents can be written as [22]

$$I_{s\max} \approx I_{r\max} = \frac{V_s}{\sqrt{(\omega_s.L_\sigma)^2 + R_{cr}^2}} \quad (4)$$

To protect the power converter during the voltage dip, the fault current has to be limited less than a safe current range ( $I_{\text{limited}}$ ), as follows

$$\frac{V_s}{\sqrt{(\omega_s.L_\sigma)^2 + R_{cr}^2}} \le I_{\text{limited}}. \quad (5)$$

From (5), the lower limit of crowbar resistance can be calculated as

$$R_{\min} = \frac{1}{I_{\text{limited}}} \sqrt{V_s^2 - (\omega_s L_\sigma I_{\text{limited}})^2}. \quad (6)$$

Also, to prevent excessive DC-link voltage the crowbar resistance should not be too high. The transient-state rotor current may incur excessively high rotor voltage, which must be satisfied as

$$\sqrt{3}.\frac{V_s}{\sqrt{(\omega_s.L_\sigma)^2 + R_{cr}^2}}.R_{cr} \le V_{dc} \quad (7)$$

where $V_{dc}$ is DC-link voltage.

The maximum crowbar resistance is described as

$$R_{\max} = \frac{V_{dc}.(\omega_s L_\sigma)}{\sqrt{3V^2 - V_{dc}^2}}. \quad (8)$$

Thus, this crowbar resistance can be rewritten as

$$2R_{\min} \le R_{cr} \le 2R_{\max}. \quad (10)$$

## 3. LVRT CONTROL SCHEME

To protect the power converters under grid fault conditions, the low voltage ride-through solution with the crowbar is applied. To decide when the crowbar is activated and the rotor-side converter is blocked, the system monitors the relevant parameters such as the rotor current, the stator current, the DC-link voltage. When at least one of these parameters is not normal value, the RSC is blocked, and the crowbar is activated, where the rotor is short-circuited through crowbar resistance. The rotor current must be reduced due to the increased rotor resistance. On the other words, this inrush current does not go through the RSC during the grid fault, but flows through the crowbar resistance (DFIG can work as if conventional induction generator), and thus does not destroy the converter. When the RSC is blocked, it is considered to work in mode 2. It means that the stator active power of the DFIG is controlled to be zero under the grid fault. Meanwhiles, GSC controls the reactive power to meet the grid requirement through reactive current calculation ( $I_d^*$ ) [1]. Also, a braking chopper (BC) is also directly involved for limiting the over-voltage of the DC link. When the grid voltages has returned to normal values, the crowbar resistance is disconnected and the RSC the rotor-side converter returns to normal control mode (mode 1).

The control block diagram of DFIG wind turbine system is shown in Figure 6. During normal grid condition, DFIG wind turbine system works in mode 1, whereas in case of grid fault condition, DFIG wind turbine system operates in mode 2.

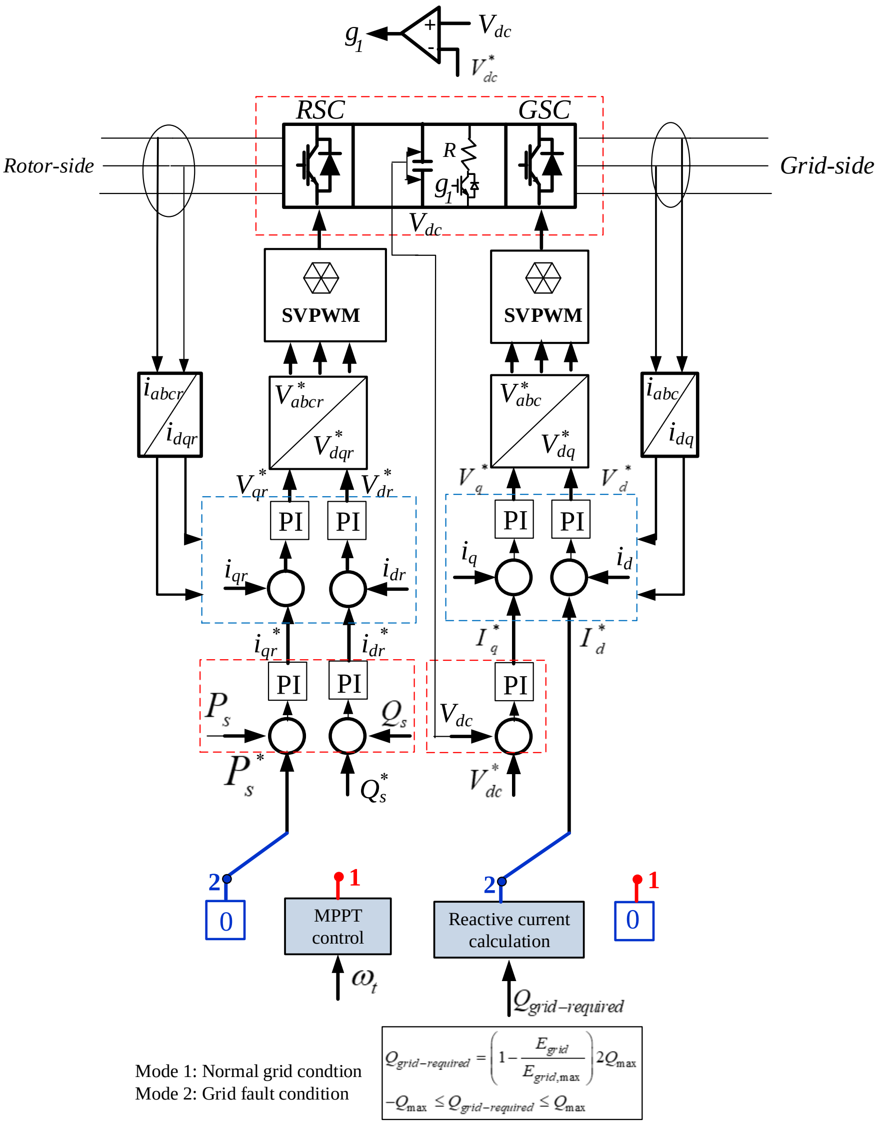


*Figure 6*. Control block diagram of DFIG

## 4. SIMULATION RESULTS

PSCAD simulation has been carried out for a 2 MW-DFIG wind turbine system in order to verify the effectiveness of the proposed method. The parameters of the wind turbine and generator are given in Table 1 and 2, respectively.

*Table 1*. Parameters of wind turbine

| Parameter | Symbol | Value |
|---|---|---|
| Rated power | $P_{rated}$ | 2 MW |
| Blade radius | R | 45 m |
| Air density | ρ | 1.225 kg/m$^3$ |
| Max. power conv. coefficient | $C_{pmax}$ | 0.4 |
| Cut-in speed | $V_{w\_in}$ | 3 m/s |
| Cut-out speed | $V_{w\_out}$ | 25 m/s |
| Rated wind speed | $V_{w\_rated}$ | 11 m/s |
| Blade inertia | $J_t$ | 6.3×10$^6$ kg.m$^2$ |

*Table 2*. Parameters of 2 MW- DFIG

| Parameter | Symbol | Value |
|---|---|---|
| Rated power | $P_{rated}$ | 2 MW |
| Grid voltage | $V_g$ | 690 V |
| Stator voltage/frequency | $V_s$/f | 690 V/60 Hz |
| Stator resistance | $R_s$ | 0.00488 pu |
| Rotor resistance | $R_r$ | 0.00549 pu |
| Stator leakage inductance | $L_{\sigma s}$ | 0.0924 pu |
| Rotor leakage inductance | $L_{\sigma r}$ | 0.0995 pu |
| Generator inertia | $J_g$ | 200 kg.m$^2$ |

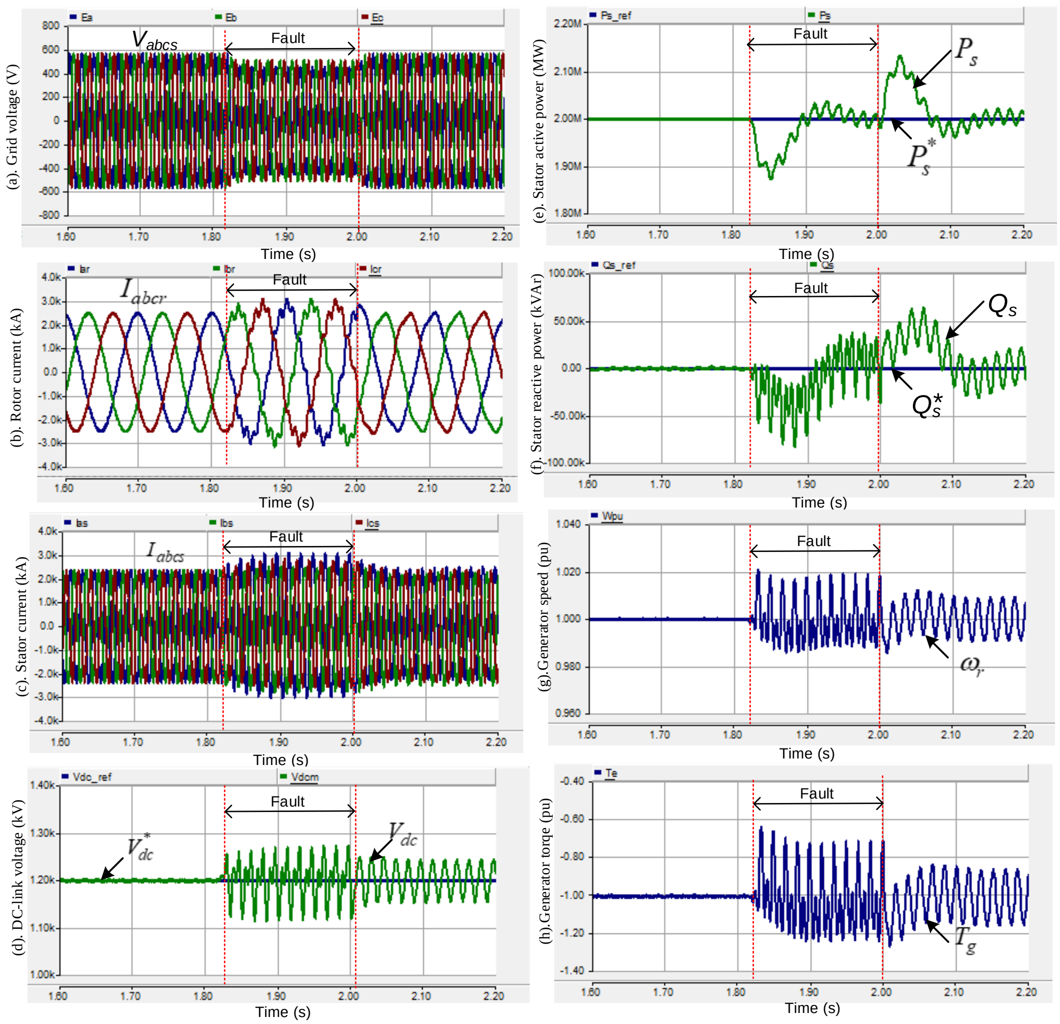


*Figure 7*. Performance of DFIG wind turbine system for unbalanced voltage sag. (a) Grid voltages. (b) Rotor currents. (c) Stator currents. (d) DC-link voltage. (e) Stator active power. (f) Stator reactive power. (g) Generator speed. (h) Generator torque.

Figure 7 shows the performance of DFIG wind turbine system for unbalanced grid voltage fault without using proposed method, where the wind speed is assumed to be unchanged (12 m/s). The fault condition is 20% drop in phase A, 10% drop in phases B and C for 0.172 s which is between 1.828 s and 2 s. When there is the grid unbalanced voltage sag as shown in Figure 7(a), the the grid voltage includes both the negative-and positive-sequence components. As illustrated from Figure 7(b) to 7(c), respectively, the stator and rotor currents are much increased. Also, as can be seen from Figure 7 (d), the DC-link voltage of the back-to-back converters without using crowbar and braking chopper reaches 1.27 kV, which can destroy the DC capacitor and the power electronics switches. Moreover, during the grid fault, the stator active and reactive powers are much oscillated, as shown from Figure 7(e) to 7(f), respectively. In addition, the generator speed and torque in Figure 7(g) and (h) have oscillations under the grid voltage fault.

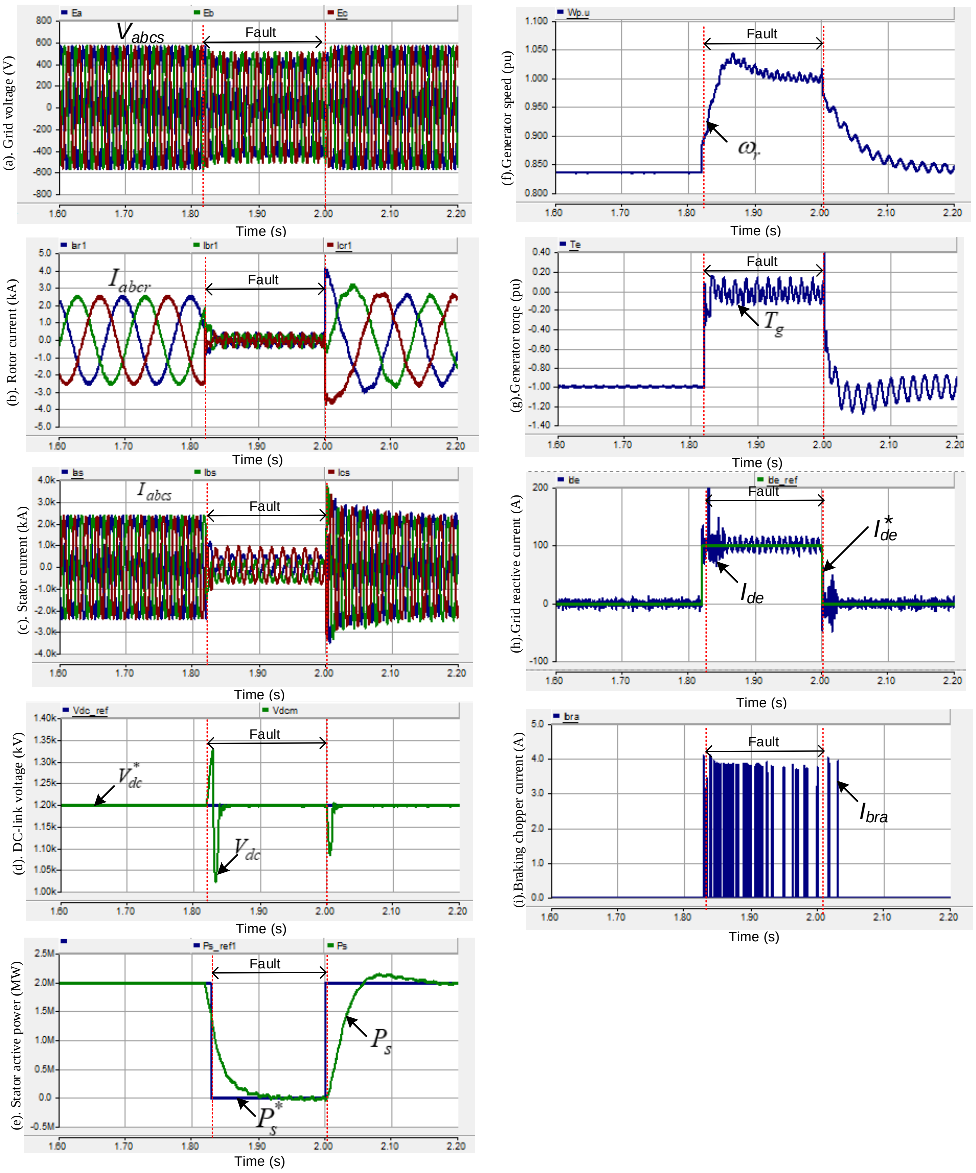


*Figure 8*. Performance of DFIG wind turbine system for unbalanced voltage sag. (a) Grid voltages. (b) Rotor currents. (c) Stator currents. (d) DC-link voltage. (e) Stator active power. (f) Generator speed. (g) Generator torque. (h) Grid reactive current. (i) Braking chopper current.

Figure 8 shows the system performance for unbalanced grid voltage fault using both crowbar and braking chopper (proposed method), in which the fault condition is similar to that of Figure 7. The stator voltage response under grid voltage fault, when applied the proposed scheme, as shown in Figure 8 (a). Due to unbalanced voltage drop, as illustated in Figure 7 (b) and (c), respectively, the stator and rotor currents are much decreased. It is clear that the performance of DC-link voltage in the proposed scheme during the grid fault is much better than that in Figure 7(d), without any crowbar and braking chopper. At beginning time of grid fault, its waveform of DC-link voltage has an increase, but inconsiderably. In this case, the stator active power (Figure 8(e)) is controlled to be zero for grid voltage recovery. Thus, the generator speed and torque, as shown in Figure 8(f) and (g) also reach around zero under the grid voltage fault. Also, the reactive power generated from the GSC is controlled to support the grid recovery through the reactive current (Figure 8(h). On the other hand, the DFIG still works normally regardless of the grid fault. Thus, the proposed method gives the good operation of the DFIG wind turbine system during the grid fault.

## 5. CONCLUSION

In this paper, the application of a crowbar connected at the rotor-side of the DFIG and a braking chopper (BC) connected in paralell with DC-link capacitor of back-to-back converters under grid voltage faults is introduced. With the proposed method, a crowbar enables to improve response of the DFIG wind turbine system during the grid faults. Also, to prevent the overvoltage caused by DC capacitor, a braking chopper has been used. The simulation results based on PSCAD software for 2 MW-DFIG wind turbine system during the grid faults have been implemented to verify the proposed method.

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**ABSTRACT**

KHẢ NĂNG LƯỚT QUA ĐIỆN ÁP THẤP CỦA HỆ THỐNG TUA BIN GIÓ DFIG DỰA VÀO CROWBAR VÀ BRAKING CHOPPER

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Bài báo này đề xuất khả năng lướt điện áp thấp (LVRT) cho hệ thống tua bin gió (WT) dùng máy phát không đồng bộ nguồn kép (DFIG). Với phương pháp được đề xuất, bộ crowbar được kết nối ở phía rotor của DFIG và bộ braking chopper (BC) được kết nối song song với tụ điện DC-link của bộ biến đổi back-to-back đã được áp dụng, cho phép cải thiện đáp ứng của hệ thống tua bin gió dùng máy phát DFIG suốt sự cố lưới. Ngoài ra, để bảo vệ tụ điện DC khỏi quá điện áp, braking chopper đã được sử dụng. Kết quả mô phỏng cho hệ thống tua bin gió 2 MW-DFIG khi có sự cố lưới được trình bày, cho kết quả vận hành tốt.

*Từ khóa:* Crowbar, braking chopper (BC), máy phát không đồng bộ nguồn kép (DFIG), khả năng lướt qua điện áp thấp (LVRT), sự cố lưới, tua bin gió (WT).