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LVRT Capability Enhancement of an Egyptian Electrical Grid Linked to the Al-Zafarana Wind Park using Crowbar and dc-chopper

Ali H. Kasem Alaboudy[1], Heba A. Mahmoud[2], Adel A. Elbaset[3], Montaser Abdelsattar[4]

[1] Electrical Department, Faculty of Technology and Education, Suez University, Suez, Egypt.
[2]Electrical Department, Faculty of Technology and Education, Sohag University, Sohag, Egypt.
[3]Electrical Engineering Department, Faculty of Engineering, Minia University, Egypt.
[4] Electrical Engineering Department, Faculty of Engineering, South Valley University, Qena, Egypt.

ABSTRACT

The connection of the doubly-fed induction generator (DFIG) wind turbines to the grid, and their dynamic behavior under different grid faults has become an important issue in recent years, and grid codes have been introduced, which is a challenge for wind energy conversion systems (WECS). One of the most important issues related to grid codes is the low-voltage ride-through (LVRT) of wind farms. Based on such code requirements, wind turbine generators must remain connected to the grid and actively contribute to the system's stability during various grid fault scenarios that result in a generator terminal voltage dip. This paper introduces the design and simulation of the protection scheme using the crowbar and dc-chopper to improve LVRT capacity for the Egyptian power grid connected to the zafarana Egypt wind system. The proposed performance of the protection scheme is verified by simulating the model using the MATLAB/SIMULINK environment. The simulation results showed that the proposed protection scheme is efficient in terms of simplicity in construction and cost efficiency. In addition, the performance of the DFIG is highly improved during the symmetrical and asymmetrical grid faults. Thus making the electrically grid-connected wind energy system more efficient by improving the capacity of LVRT.

Keywords: Wind Turbine; DFIG; LVRT; Zafarana Egypt Wind System; Protection Scheme.

1. INTRODUCTION

In recent years, electrical generation using wind energy (WE) has increased in most countries that have windy regions; wind energy has obtained the fastest growth, and the cumulative installed capacity of wind power generators all over the world may be more than 800 GW by 2021 [1, 2]. Note that energy quality is a significant feature that affects the stability and security of electric power systems, and it is very crucial to stabilize wind power generators under short-circuit faults. Wind turbines (WTs) should keep the grid-connected status for a certain time, and this Condition depends on the severity of faults or level of voltage sags to meet specific code demands, so-called low-voltage ride-through (LVRT) operation. As the most widely used WT, the doubly fed induction generator (DFIG) has obtained considerable attention, in part because DFIG-based wind generation operates with variable wind speeds and provides fixed-frequency power with high reliability. It enables the control of active and reactive powers injected into the grid system [3].

However, DFIG has suffered from voltage fluctuations, converter damage, mechanical oscillations, and stresses. Therefore, wind generation should provide ancillary services for power grids and enforce LVRT for large wind generation to improve the reliability of the power system. Many research studies have been conducted to address these issues, and numerous measurements for the LVRT enhancement of DFIG have been proposed. Generally, the existing methods are classified as software and hardware approaches [4]. For instance, an advanced current tracking controller is applied in the rotor-side converter (RSC) [5]. Researchers discussed how to determine a proper tracking coefficient for the controller, and the results show the transient fluctuations in the RSC can be well constrained. In Ref. [6], an available generator-side converter (GSC) voltage is utilized to conduct the

Co-Author; Heba A. Mahmoud, Heba_Ahmed123@techedu.sohag.edu.eg
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voltage compensation, and the DFIG's transient flux is controlled to obtain a desirable fault current limitation. In Ref. [7] a linear-quadratic regulator is implemented in the DFIG

This regulator serves as a supplementary control to prevent converter saturation. In Ref. [8], an optimal hierarchical control structure is proposed. The primary and secondary control levels are designed, and it is found that active and reactive power oscillations in the generator can be favorably mitigated, as mentioned in Refs. [9–10]. Two improved controllers based on fuzzy logic are used in the RSC, and the key functions of the proposed controllers are to decrease the rotor current and inhibit the DC-link voltage. In Ref. [11], scholars investigate an analytical method to determine the control parameters of the DFIG subject to the capacity limit of the RSC. Overall, the transient stability support from the software solutions towards the DFIG may be relatively moderate, and the improvements of optimizing current reference and introducing over-modulation could be appreciatively done, the software solution is regarding an improved or updated control strategy with less cost, but it is just suitable for handling moderate fault conditions.

In the following, the hardware solutions based on the chopper circuit, voltage compensator/restorer, and FCL are reviewed. In Ref. [12], the effectiveness of a DC-link chopper in decreasing the DC overvoltage is validated; nevertheless, it fails to assist in the demagnetization of the electrical machine post-fault. Ref. [13], proposes a modified DC chopper that can be inserted in a DFIG base series or parallel connection. Although the modified structure makes certain improvements, the rotor current is still around its safety limit (2.0 pu). In Ref. [14], a minimized series voltage compensator is applied. Since the stator flux is well controlled, the generator is allowed to ride through the grid disturbances as mentioned in the Refs. [15–17], and a bridge-type FCL with a bypass resistor is applied in a DFIG.

The research results confirm its positive effects on reducing flux and electromagnetic torque oscillations. It is worth stating that, a few preliminary studies on the coordination control of a fault current limiter and an energy storage device for stabilizing a DFIG have been reported in Refs. [18–22]. It is revealed that the combined utilization of two devices with different functions can bring more contributions to enhancing the transient characteristics of a DFIG. In a sense, developing this kind of study and exploring a novel combination scheme with preferable potentials are of significance. Furthermore, the hardware solution is to use one or more devices that require a costly investment and have a good ability to deal with severe short-circuit faults.

This paper proposes a protection scheme using the crowbar and dc-chopper to improve the LVRT capacity for the Egyptian power grid connected to the Zafarana Egypt wind system. The protection scheme ensures the safety of energy converters, rotor circuits, and dc-link capacitors. The protection system is simulated with the MATLAB/SIMULINK tool to verify the finding.

In this paper, Section 2 presents an overview of the modeling of grid-connected DFIG wind turbines. Section 3 explains the configuration of the crowbar and DC-chopper and its effects on the DFIG. The simulation findings and the impact of the crowbar and DC-chopper scheme on DFIG are discussed and evaluated in Section 4. The conclusions are offered in Section 5.

2. SYSTEM CONFIGURATION

The Al Zafarana wind farm is situated southeast of Cairo, Egypt, along the Red Sea coast. The farm was developed and organized into seven stages, each requiring 30, 33, 30, 47, 80, 85, and 120 MW. The fifth stage of the farm is considered in this study for simulation purposes. The structure is made up of 100 wind turbine generators (WTGs) of varying speeds (each with an 850 KW DFIG unit). There is a 690V/22kV step-up transformer linked to each WTG. Three 75 MV, 22/220 kV main step-up transformers are then used to feed the electrical energy collected into the Egyptian power grid at 220 kV, as depicted in Fig. 1.

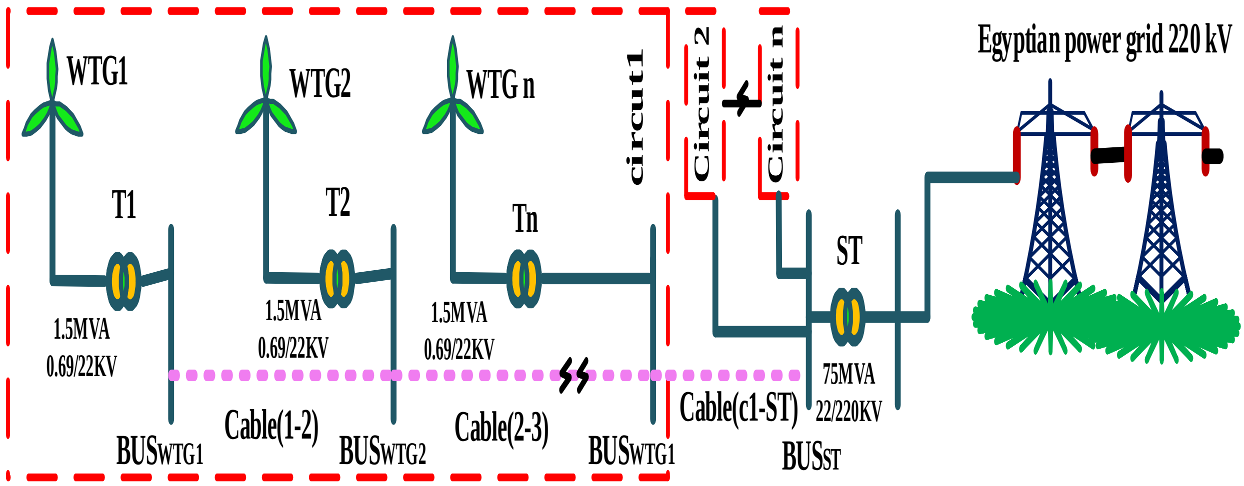

Fig. 1: Simplified layout of fifth stage of Al-Zafarana wind farm

2.1 Wind turbine model

According to wind turbine generators" (WTGs) characteristics, mechanical power is given by the following relations:

$$P_m = \frac{1}{2} C_p(\lambda, \beta)\rho A_t V_\omega^3 \quad (1)$$

Where: ρ is the air density, A is the swept area of a wind turbine, Vω is the wind speed, Cp is the power coefficient, β is the blade pitch angle, and λ is the ratio between the turbine angular speed and the wind speed.

$$\lambda = \frac{R\,\omega_t}{V_\omega} \quad (2)$$

Where: R is the turbine radius; ωt is the turbine rotational speed. The power coefficient Cp value is approximated according to the non-linear function

$$c_p = 0.22\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right) e^{-12.5/\lambda_i} \quad (3)$$

With $\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^2 + 1}$

2.2 .Double-fed induction generator model

Nowadays, the DFIG is the most used wind power system in wind energy farms. The basic configuration of a The DFIG model is shown in Fig. 2. DFIG stator winding typically connects directly to the grid, while rotor winding is connected via slip rings to power converters [23]. The power electronic converter connecting the rotor windings to the grid consists of two voltage-source converters, i.e., the rotor-side converter (RSC) and grid-side converter (GSC), Between the two converters, a DC-link capacitor is placed as energy storage to keep the voltage variations (or ripple) in the DC-link voltage small. By referring to [24], the modeling equations are formulated as follows:

$$\vec{V_s} = R_s\,\vec{i_s} + d\vec{\psi_s}\,/\,d_t + j\omega_s\,\vec{\psi_s} \quad (4)$$

$$\vec{V_r} = R_r\,\vec{i_r} + d\vec{\psi_r}\,/d_t + j(\omega_s - \omega_r)\vec{\psi_r} \quad (5)$$

$$\vec{\psi_s} = L_s\,\vec{i_s} + L_m\,\vec{i_r} \quad (6)$$

$$\vec{\psi_r} = L_m\,\vec{i_s} + L_r\,\vec{i_r} \quad (7)$$

Where, $\vec{i}$, $\vec{V}$, $\vec{\psi}$, ***R***, ***L*** are the current, voltage, flux, resistance as well as inductance, respectively. Subscripts s, r are the stator and rotor, respectively. It is obtained that $L_s = L_{s\sigma} + L_m$ and $L_r = L_{r\sigma} + L_m$, and $L_{s\sigma}/L_{r\sigma}$ is the leakage inductance. From Eqs. (3) and (4), the stator and rotor currents are signified as:

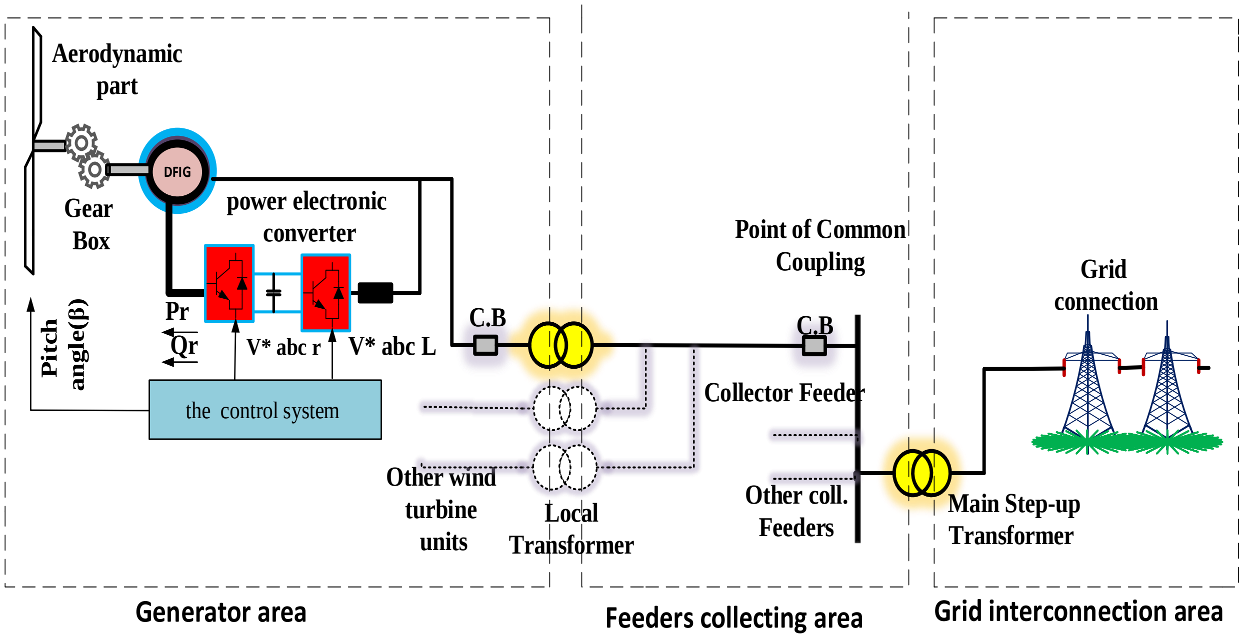

Fig 2: The schematic diagram of the grid-connected DFIG WT system.

$$\vec{i_s} = \vec{\psi_s}/\dot{L_s} - K_r \vec{\psi_r} / \dot{L_s} \quad (8)$$

$$\vec{i_r} = -K_s \vec{\psi_s}/\dot{L_r} - \vec{\psi_r} / \dot{L_r} \quad (9)$$

Where, $\dot{L_s} = L_s - L_m^2/L_r$ and $\dot{L_r} = L_r - L_m^2/L_s$ are deduced; $K_s$and $K_r$are expressed as $K_s = L_m/L_s$ and $K_r = L_m/L_r$ respectively.

Figure 3shows the control block diagram of the DFIG converters. For the DFIG, the rotor-side converter applies the voltage to the rotor windings for excitation to control the rotor currents such that the rotor flux position is optimally oriented with respect to the stator flux in order that the desired torque is developed at the shaft of the machine. The vector control for the generator can be embedded in an optimal power tracking controller for maximum energy capture in a wind power application [25]. By controlling the active power of the converter, it is possible to vary the rotational speed of the generator, and thus the speed of the shaft of the wind turbine [26].

This can be used to track the optimum tip-speed ratio as the incident wind speed changes thereby extracting the maximum power. Also, it provides a varying-frequency excitation depending on the wind speed conditions. The induction generator is controlled in a synchronously rotating dq-axis frame, with the d-axis oriented along the stator-flux vector position in one common implementation. This is called stator-flux orientation (SFO) vector control. Consequently, the active power and reactive power are controlled independently from each other. The grid side converter is to keep the DC-link voltage constant (this means that observer of DC-link voltage) and that is through enabling independent control of the active and reactive power flowing between the grid and the grid side converter [27].

2.3 Steady-state operation

In steady state, the power exchanging between the DFIG and the grid is depending upon the rotor slip "s" and weather the machine speed is either over or below the synchronous speed. The mechanical, electrical power and the slip (s) of the DFIG could be obtained from the following equations:

$$p_r = p_m - p_s = T_m\omega_r - T_m\omega_s$$
$$= -T_m\left(\frac{\omega_s - \omega_r}{\omega_s}\right)\omega_s$$
$$= -sT_m\omega_s = -Sp_s \quad (10)$$

Where, S is defined as the slip of the generator:

$$S = \frac{\omega_s - \omega_r}{\omega_s} \quad (11)$$

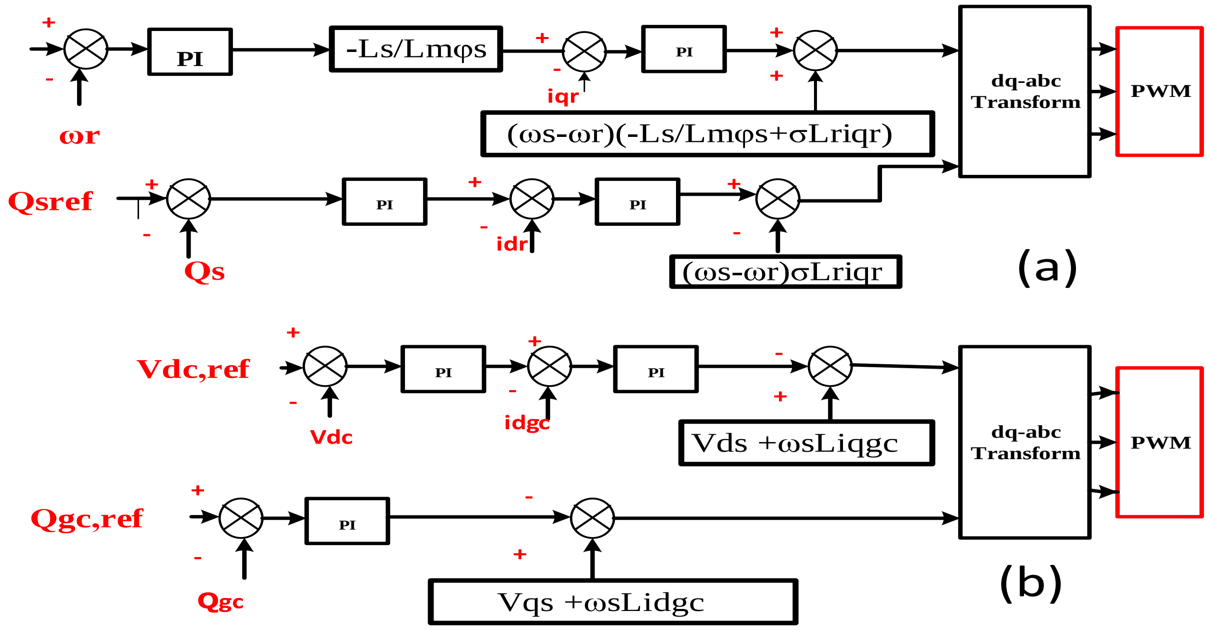

Fig 3: Control block diagram of the DFIG converters. **(a)** RSC, **(b)** GSC.

The stator and rotor power are $P_s = P_m/(1–S)$ and $P_r = –S\ P_m/(1–S)$. Therefore, if the maximum slip is limited, say to 0.3, the rotor winding converters can be rated as a fraction of the induction generator rated power. This is typically around ±30% for DFIG in wind power generation systems and gives a slip range of ±0.3. The slip is assumed to vary from a sub-synchronous value of +0.35 to a super-synchronous value of –0.35. The rotor and stator power vary as the rotor slip changes from sub- to super-synchronous modes. Thus, the operating modes of DFIG as follows:

- **In the sub-synchronous mode** at lower wind speeds, the blades rotate at a sub-synchronous speed ($\omega r < \omega s$), $s > 0$). In this case, the rotor converter system will absorb power from the grid to provide excitation for the rotor winding. Where a stator circuitry is fed with active power.
- **In the super-synchronous mode** the machine operates at super-synchronous speeds ($\omega_r > \omega_s$), $s < 0$). In this case, both stator and rotor generated powers are fed to the grid (So it's called the doubly-fed induction generator (DFIG).
- **In the synchronous mode** When rotating at the synchronous speed ($S = 0$), the DFIG supplies all the power via the stator winding, with no active power flow in the rotor windings.

3. Configuration of the Crowbar and DC-chopper and its Effects on the DFIG

The protection scheme contains two protection circuits: a DC-chopper and crowbar as shown in Fig. 4. A crowbar is a set of resistors that are connected in parallel with the rotor winding. The crowbar firing is triggered by increasing the value of rotor current with blocking the converter during the fault. Thus, the current continues to flow into the DC-link through the freewheeling diodes leading to a very fast voltage increase. The DC-chopper is switched on for limited over voltages. In the past years, many researches have been presented to use crowbar protection to protect the converter. However, the results are shown for the symmetrical grid faults. However in this paper, the protection circuits has been improved in order to benefit from resistors to reduce rotor current and DC-link overvoltage with the converter is blocked during the symmetrical and asymmetrical grid faults. Where the specific values of resistors for each of the crowbar (R_{CB}) and DC-chopper (R_{DCC}) are 10kΩ and 11Ω respectively.

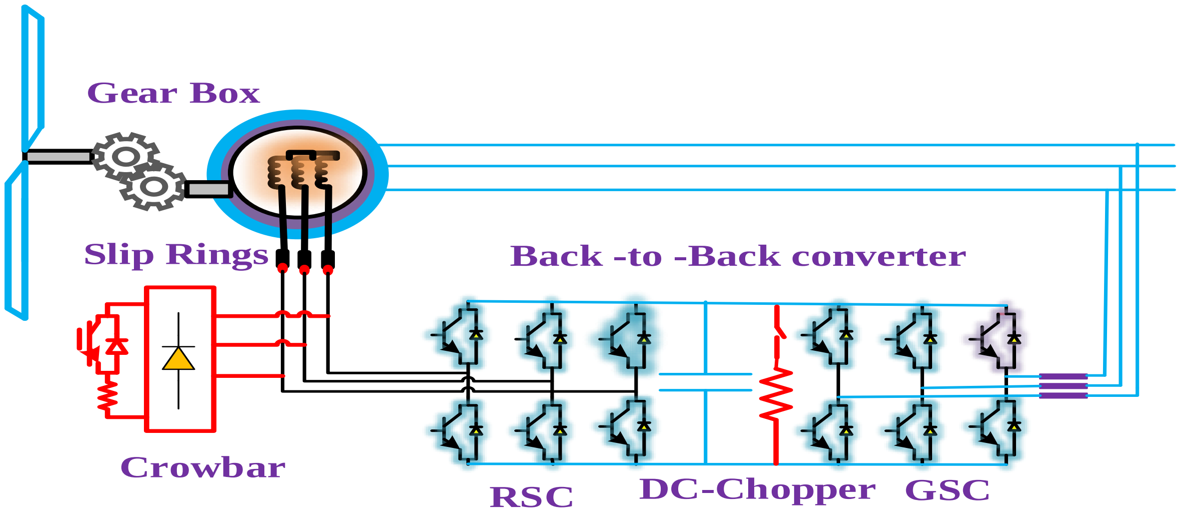

Fig 4: Topological structure of the Crowbar and DC-chopper protection scheme.

4. SIMULATION ANALYSIS

To validate the effectiveness and feasibility of the protection schemes, simulation analyses are done in MATLAB. Figure 5 shows a single line diagram for the system. The simulation work has been performed for wind farm that is connected to a distribution system and exports power to a 220 KV grid.

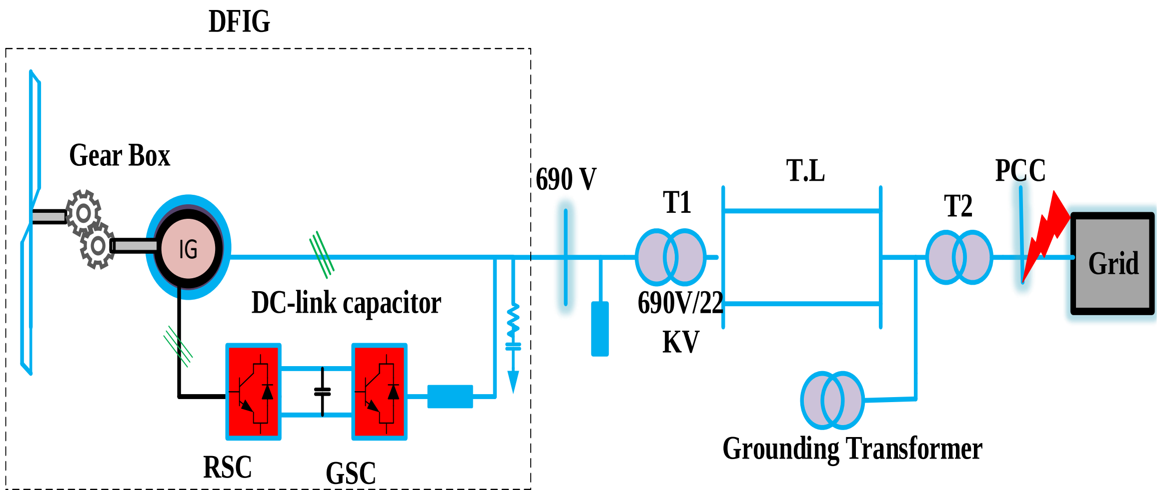

Fig 5: Single line diagram for the studied system.

4.1 Study of the asymmetrical fault

It is simulated that, a three-phase fault occurs at the grid connection point as the fault starts at time (t = 0.7s) and cleared at t = 0.9s as show in Fig. 6 the system response at 0.95pu voltage dip for 0.2s with crowbar and DC-chopper protection. The crowbar firing is triggered by the rotor currents which rise due to the first rotor current peak. The electronic switches of the converter are usually stopped by the protection. However, the current and thus the energy continue to flow into the DC-link through the freewheeling diodes leading to a very fast voltage increase. Thus, the DC-chopper is switched on to limit overvoltage. The included parallel resistance in the rotor circuit and also connected resistance in parallel with DC-link result in decreasing the stator currents from 2.66pu to 1.81pu for the most serious phase. The rotor currents are decreased from 2.5pu to 1.42pu for the most serious phase. The DC-link voltage and electrical torque fluctuations are significantly reduced.

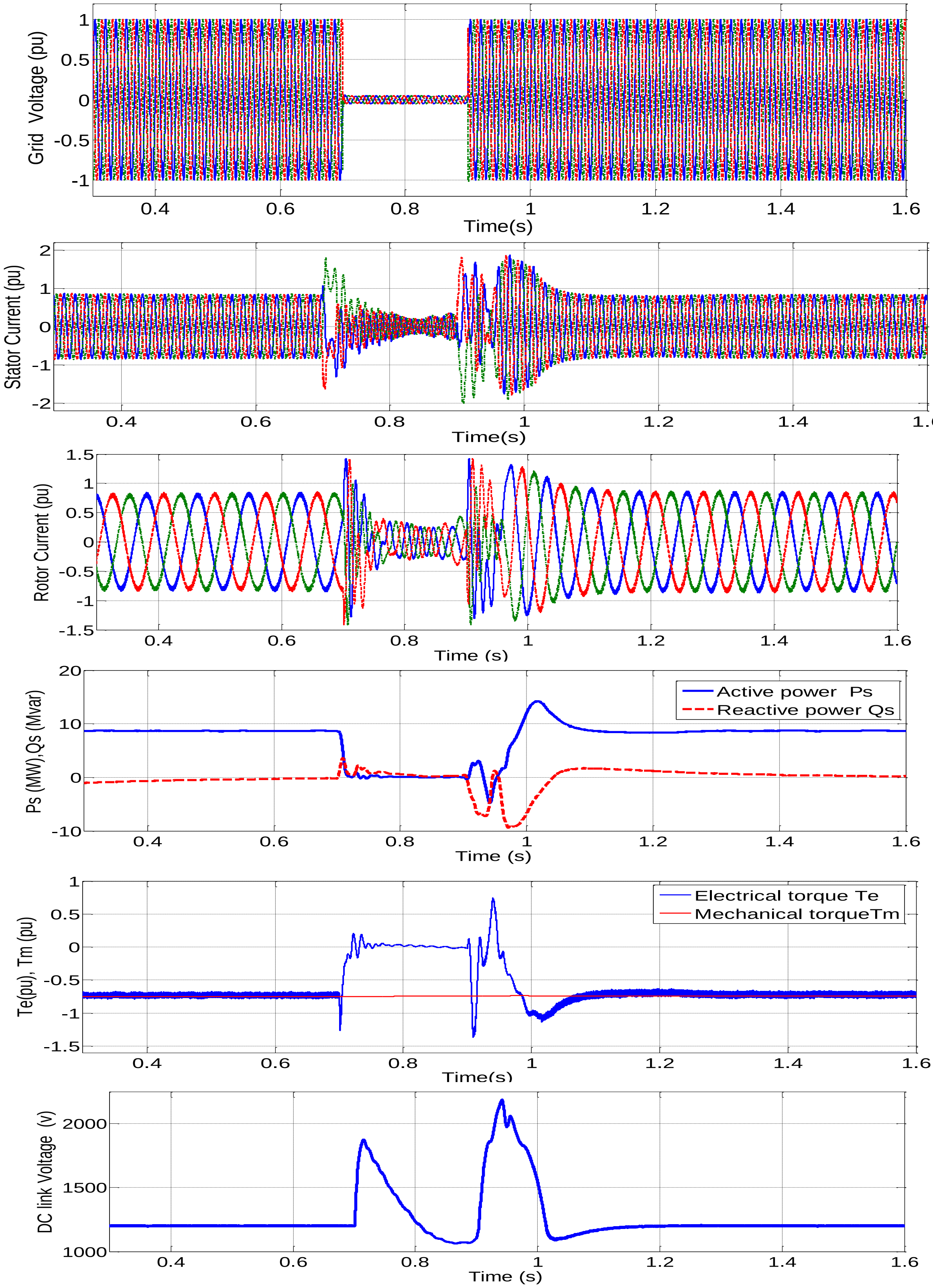

Fig 6: Three-phase 0.95pu voltage dip for 0.2s with crowbar and a DC-chopper protection scheme.

4.2 Study of the asymmetrical fault

Figure 7 shows the system responses during asy)mmetrical fault conditions. The phase b and c are short-circuited. When the DC chopper and the crowbar switches are triggered on simultaneously, the stator currents are reduced from 2.09pu to 1.38pu for the most serious phase. The rotor currents are decreased from 1.91pu to 1.06pu for the most serious phase resulting significantly reducing the DC-link voltage and electrical torque fluctuations.

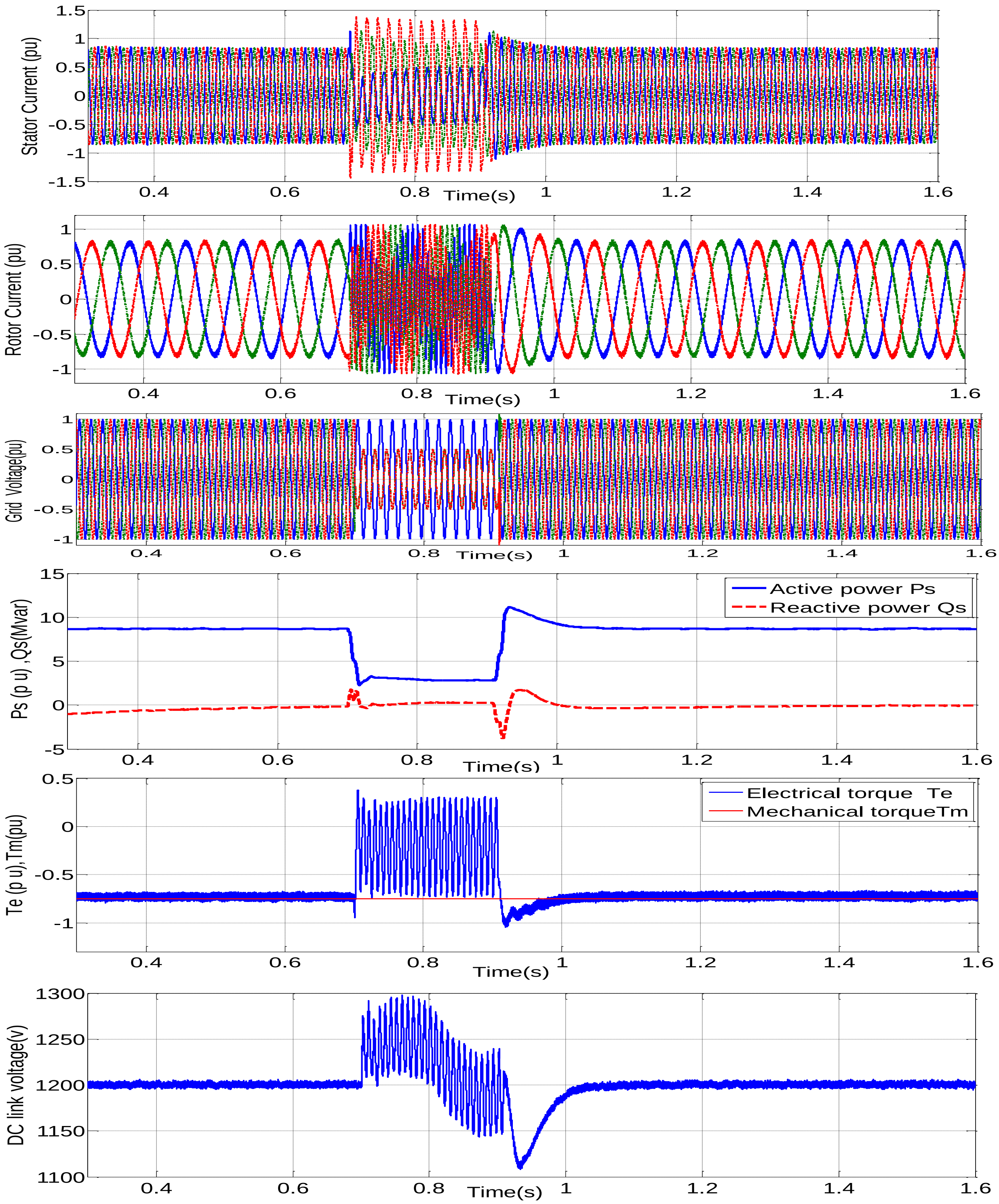

Fig 7: Phase *b* to *c* short circuit for 0.2s with crowbar and a DC-chopper protection scheme

5. CONCLUSION

In this study, protection schemes are investigated to enhance the DFIG-based wind turbines' performance. Grid faults have a strong impact on both the mechanical and electrical components of the wind turbine. The purpose of the protection scheme is to reduce the voltage induced in the rotor circuit during the fault occurrence.The crowbar and DC-chopper protection are more effective in terms of damping current increases at the generator terminals. In addition to that, the scheme is based on a simple concept. It decreases the cost and complexity of the system. It is useful under symmetrical and asymmetrical grid faults as it decreases the rotor overcurrent, DC-link overvoltage, and torque oscillations compared to the other scheme. Hence, it contributes to system stability during grid faults.

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تحسين قدرة LVRT لشبكة الكهرباء المصرية المرتبطة بحديقة الرياح الزعفرانة باستخدام Crowbar و DC-Chopper

الملخص

أصبح توصيل تور بينات الرياح ذات التغذية المزدوجة (DFIG) بالشبكة، وسلوكها الديناميكي تحت أعطال الشبكة المختلفة مشكلة مهمة في السنوات الأخيرة، وتم إدخال رموز الشبكة، وهو ما يمثل تحديًا لأنظمة تحويل طاقة الرياح (WECS)واحدة من أهم القضايا المتعلقة برموز الشبكة هيLVRT لمزارع الرياح. بناءً على متطلبات الكود هذه، يجب أن تظل مولدات تور بينات الرياح متصلة بالشبكة وتساهم بفعالية في استقرار النظام أثناء سيناريوهات أخطاء الشبكة المختلفة التي تؤدي إلى انخفاض جهد المولد. يقدم هذا البحث تصميم ومحاكاة مخطط الحماية باستخدامcrowbar and dc-chopperلتحسين قدرة LVRT لشبكة الكهرباء المصرية المتصلة بنظام الرياح الزعفرانة مصر. يتم التحقق من الأداء المقترح لنظام الحماية عن طريق محاكاة النموذج باستخدام بيئة .MATLAB / SIMULINK أظهرت نتائج المحاكاة كفاءة مخطط الحماية المقترح من حيث البساطة في البناء وكفاءة التكلفة. بالإضافة إلى ذلك، تم تحسين أداء DFIG بشكل كبير أثناء أعطال الشبكة المتماثلة وغير المتماثلة. وبالتالي جعل نظام طاقة الرياح المتصل بالشبكة الكهربائية أكثر كفاءة من خلال تحسين قدرة.LVRT