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Improved Protection Schemes for DFIG Based Wind Turbines during the Grid Faults

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Abstract: *There are many negative impacts of the grid faults in Doubly Fed Induction Generators (DFIG) based wind turbines such as stator and rotor over currents, DC-link over voltage, electromagnetic torque oscillations, active and reactive power fluctuations at the grid connection point. Negative impacts of the grid faults have potentially led to destabilization of the power system network. Eliminating the negative impacts enhances the DFIG based wind turbines performance. This paper proposes a comprehensive study about the performance analysis and protection of a 1.5MW DFIG-based wind turbine in order to keep the wind turbine connected to the grid under the symmetrical and asymmetrical grid faults. This study discusses and compares the simulations of two improved protection schemes to eliminate the negative impacts of the grid faults. The investigated protection schemes are simple in construction and cost efficient. The performance of the DFIG is highly improved during the grid faults. The simulation results confirm the effectiveness of these schemes.*
Keywords : *Wind Energy, Wind Turbines, DFIG, Protection schemes.*

I. Introduction

Wind has stood out to be one of the most renewable promising alternative sources of electrical power. It is environmentally friendly as means to deal with the world energy shortage. It is now considered as an actual alternative to the conventional and polluting energy sources such as oil, gas, and coal [1]. According to WWEA, a power capacity more than 50GW were added during 2014, bringing the total wind power capacity close to 370GW [2].

The capture of wind power using the installed fixed speed wind turbines has a number of drawbacks. They can only operate within a very narrow speed range above the synchronous speed, and consume reactive power. As a result of being directly connected to the grid. Wind speed variations are directly translated into voltage and power fluctuations at the grid connection point, potentially leading to destabilization of the power system network [3-5].

While these turbines are practically obsolete, they are used at a number of older wind farms. They are not expected to be replaced by modern wind turbines until they reach the end of their economic life, typically around 20 to 25 years from installation [4]. Most of the aforementioned drawbacks are avoided when variable-speed wind turbines are used. These turbines improve the dynamic behavior of the turbine and reduce the noise at low wind speeds. The power production of variable-speed turbines is higher than fixed-speed turbines. In addition to that, the produced energy is of better quality, as they can rotate at the optimal rotational speed for each wind speed. Other advantages of variable-speed wind turbines are that they reduce mechanical stresses, and that they compensate for torque and power pulsations. Variable speed turbines are now prevailing, as their performance is superior and are considered likely to constitute a large portion of the mix generation for wind farms [5].

Variable-Speed Wind Turbines, the most cost-effective and widely used across the new installations in the last few years, are based on DFIG. They use power converters rated to a fraction of the total power. Therefore, the losses in the converter can be reduced and the cost of the converter becomes lower [6]. This has the capability to generate and consume active and reactive power in a controlled manner. The rotor converter allows independent control of the wind turbine active and reactive power.

Variable-Speed Wind Turbines based on DFIG can operate above and below the machine's synchronous speed. Above the synchronous speed, the rotor converter injects active power to the grid. However, below the synchronous speed the power is consumed in the rotor from the grid. This provides an operating speed range of around ±25–35% of the rated speed [4]. Another advantage of this type is that the mechanical drive train is largely decoupled from the electrical system via the back-to-back converter. This means that variations in the prime mover do not have a pronounced impact on the grid. Hence, the flicker levels and the power factor control for the overall system are reduced.

However, variable-speed wind turbines based on the DFIG are very sensitive to grid voltage disturbance for symmetrical and asymmetrical voltage dips as described in [7, 8]. For a sudden symmetrical or asymmetrical drop of the grid voltage, the DFIG stator currents dramatically increase beyond the rated values. Because of the magnetic coupling between stator and rotor, the stator fault currents are transmitted into the rotor causing uncontrollable excessive rotor over-currents. These currents can damage the power electronic devices of the power converter. Also, the electromagnetic torque of the DFIG starts to oscillate with high amplitudes causing mechanical stresses to the wind turbine system [9].

Initially, the solution implemented by the manufacturers to protect the power converter was to short circuit the rotor windings with the so-called crowbar and disconnect the turbine from the grid. With this solution, they contribute to increase the voltage dip as they stop generating electric power. For example, the European outage on November 4, 2006, caused the disconnection of 2800 MW of wind-origin power in Spain [10]. Thus, these renewable generators unlike conventional power plants will not be able to support the voltage and frequency of the grid during and immediately following the grid failure. This would cause major problems for the systems stability.

It is therefore worldwide recognized that to enable large-scale application of wind energy without compromising system stability, the turbines should stay connected to the grid in case of a failure. They should be similar to conventional power plants. Therefore, researchers are addressing the issue from several points of view. These points of view can be divided into two categories: improving the DFIGs converters conventional control and the extra hardware based protection schemes. The first is a means of designing more advanced control strategies for the rotor and grid side converters [11]–[19].

However, some of these algorithms have a number of drawbacks. They are too complicated to implement in industrial applications. Also, they depend strongly on the proper design of the control parameters or the estimation of certain parameters, which may have adverse effects on its robustness. This makes the control systems complex and increases the issues with control coordination between normal and fault operation. The disadvantage of the variable-speed turbine is the more complex electrical system. The other demerit is the extra hardware modification such as the related modifications based on the conventional crowbar protection. Some improved crowbar solutions have been proposed to enhance the low voltage ride-through (LVRT) performance of the DFIG based wind turbine [20]–[25].

The crowbar circuit short-circuits the rotor terminals and isolates the Rotor-Side Converter (RSC) from the rotor that provides conservative protection to the RSC. At the same time, it changes the DFIG to a squirrel cage induction generator, which absorbs reactive power from the grid when reactive power support is required. As result, several installation are implemented at the DFIGs terminals to provide reactive power during the grid faults static and dynamic such as VAR compensators or STATCOMs, dynamic voltage restorers [26, 27], flexible alternating current transmission systems (FACTSs) [28, 29], and resistors [30]-[33]. However, these solutions increase the complexity and cost of the wind turbines system. The most of the approaches show results for the symmetrical grid faults, whereas majority of the grid faults in the power system are asymmetrical.

In this paper, the key ideas in improving the extra hardware based protection schemes are investigated to protect DFIG. This is achieved by analyzing two schemes. The two schemes are simple and cost efficient in order to avoid the aforementioned drawbacks. The first scheme is the series resistor (SR) protection.

A series resistor is switched in series with the rotor winding. In normal operation, it is controlled by a power electronic switch. The switch is on and the resistor is short circuit. During fault occurrence, a switch is off and the resistor is connected in series to the rotor winding. SR can share the rotor circuit voltage and hence limits the rotor over current during the fault. It is an alternative to crowbar protection.

The other scheme is crowbar and DC-chopper protection. It contains two protection circuits: a crowbar and DC-chopper. A crowbar is a set of resistors that are connected in parallel with the rotor winding. The crowbar firing is triggered with increasing the rotor current, the converter is blocked during the faults. Thus the current continues to flow into the DC-link through a freewheeling diode leading to a very fast voltage increase. A DC-chopper is switched on to limit the over voltage [34]. To benefit of the crowbar and DC-chopper resistance, both schemes are connected in parallel in the rotor circuit in order to reduce the rotor over current under symmetrical and asymmetrical grid faults.

In this paper, several practical results are obtained. For each scheme, the active and reactive powers, electromagnetic torque pulsations are investigated. Rotor and stator currents are obtained and compared for the most serious phase.

The rest of the paper is organized as follows: in section 2, effects of the grid faults upon the DFIG Based wind turbine without protection are presented. In section 3, the advanced protection schemes of the DFIG behavior under grid faults are presented and analyzed. Section 4 discusses the simulation results of the DFIG system under grid faults with using the two advanced protection schemes. Finally, the concluding remarks on the use of such protecting schemes for DFIG applications are presented.

II. Effects Of The Grid Faults On The Dfig Based Wind Turbine Without Protection

2.1 DFIG Based Wind Turbine Modeling

The block diagram of the grid connected wind energy conversion system is shown in Fig. 1. The DFIG based wind turbine system consists of the wind turbine, drive train, induction generator, back-to-back PWM converters, and control system. It is connected to the grid through a transformer. The control system consists of two control levels: wind turbine control and DFIG control. The DFIG control level includes the rotor and grid side controllers. It controls the active and reactive power of the DFIG machine using the vector control technique [35]. The Matlab/Simulink diagram of the simulated system with the corresponding parameters is given in the Appendix A.

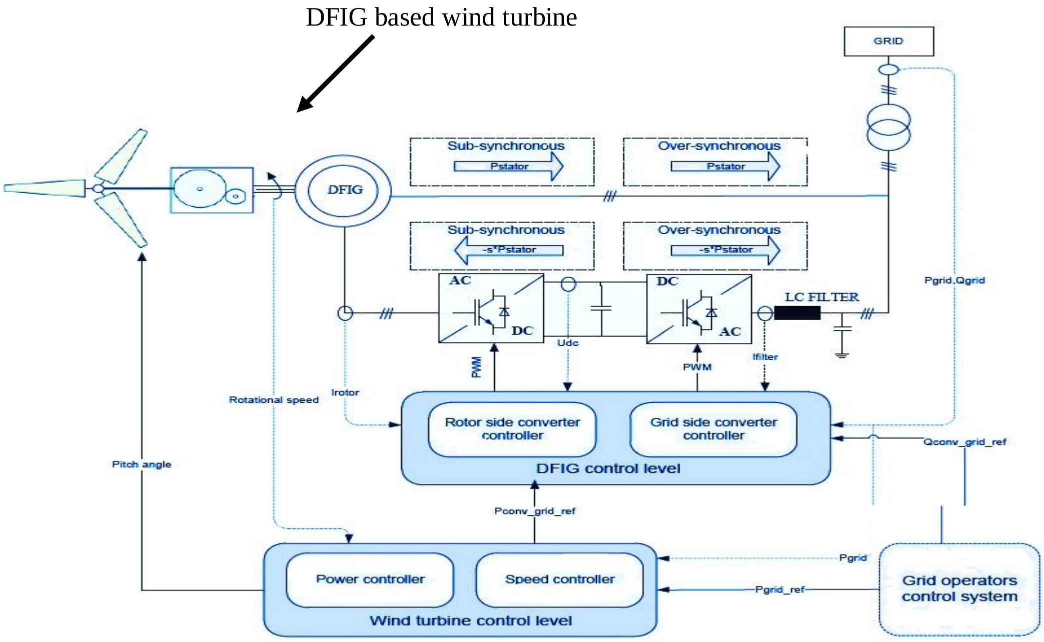

Fig. 1: Block diagram for a wind turbine control based on DFIG [36].

2.2 Effects of symmetrical and asymmetrical grid faults

The sudden voltage drops of the grid voltage results in dramatically increase in the DFIG stator currents beyond the rated values. Because of the magnetic coupling between stator and rotor, the moment change of the machine magnetic flux causing induced voltages inside the rotor circuit. The magnetic flux of the DFIG machine is divided into two components. The first component corresponds to the “forced flux” that rotates at the synchronous speed. It appears during the normal operation of the machine.

The second component is called “natural flux”. It appears during voltage dips. Each component induces voltages in the rotor. The voltage induced by the forced flux is small; it may be up to zero. During gird faults, voltages are induced by the natural flux alone. The induced voltage amplitude is proportional to the depth of the grid voltage dip and type of the fault [7, 8].

If the depth of the dip is small and the voltage induced does not exceed the maximum voltage that the rotor converter can generate, the current remains controlled, and thus there is no risk on the DFIG, as in the normal operation. However, in cases of larger dips caused by symmetric faults, the induced voltage at rotor terminals exceeds the maximum available tension of the converter and the control of the current is lost transitorily. In this situation, over currents appear. These currents represent a risk to DFIG. The currents will increase as the depth of the dip is bigger. This situation is transient and only occurs at the beginning (or end) of the dip, that is, when the grid voltages change abruptly.

In asymmetrical dips, a three-phase voltage system can be expressed as the sum of three components: positive, negative, and zero sequences. The positive and negative sequence components create fluxes. Each flux induces a voltage in the rotor. The nature of these voltages is different. Not only do they have transitory components, such as those originated in symmetrical dips, but they also have permanent components that remain throughout the whole dip. Besides, asymmetrical dips are more harmful to the generator than are the symmetrical dips since they induce higher voltages in the rotor. Those are much greater than those appearing under normal operation.

To demonstrate the important difference between symmetrical and asymmetrical faults, an extensive simulation study using the MATLAB/Simulink is conducted on a 9MW wind farm consisting of six 1.5MW DFIG-based wind turbines. To simulate the most onerous grid faults conditions that can be imposed upon the

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DFIGs, the generators operate in the super synchronous mode with rotors speed is 1.2pu before the moment of grid faults occurrence. A fault located at the connection between the point of common coupling (PCC) and the 120kV grid as depicted in Fig. 2 is simulated. The fault starts at time (t = 0.7s) and cleared at t = 0.9s. The simulated fault conditions are as follows:

1-Symmetrical fault with voltage dip of 0.95pu.

2-Two-phase asymmetrical fault (phase b to c).

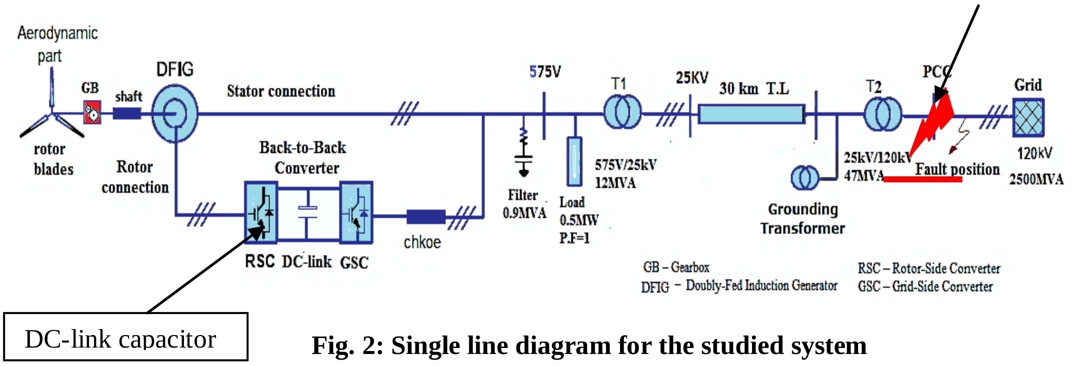


Fig. 2: Single line diagram for the studied system

(1) Symmetrical Fault With Voltage Dip Of 0.95pu

Figure 3 shows the system responses for grid voltage dip of 0.95pu for 0.2 s, As it is noticed in Fig. 3, the decreased in grid voltage considerably increases currents in the stator. In the symmetrical fault, the increase of the current only happens at the beginning (or end) of the dip. The stator currents reach around 2.66pu for the most serious phase. Voltage dips lead also appears natural flux during voltage to induce voltages in the machine rotor. In this situation, the over currents increase to around 2.5pu for the most serious phase at the beginning (or end) of the dip. This results in rising DC-link voltage. The DC-link capacitor shown in the Fig. 2 is usually not able to reduce this effect considerably. The wind turbine shaft will experience oscillating torque. The first peak of the oscillating torque reaches almost 0.7pu leading to severe stressing of the turbine shaft and fluctuations in both the active and reactive power.

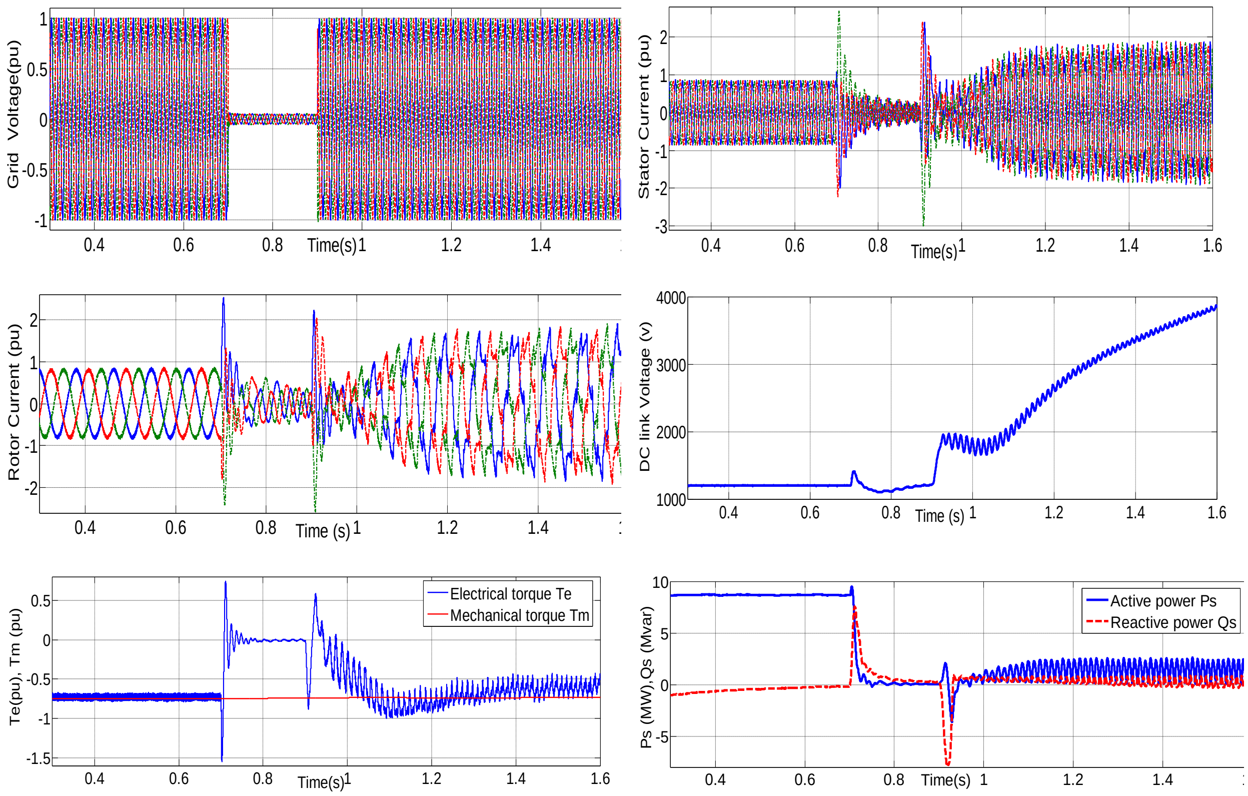


Fig. 3: Three-phase 0.95pu voltage dip for 0.2s

Two-phase asymmetrical fault (phase b to c).

Figure 4 shows the system responses during asymmetrical fault conditions. In Fig. 4, the phases b and c are shorted together for 0.2 s, leading to a voltage dip at the stator terminals. As described in the previous section, voltages are induced in the rotor. The nature of the rotor induced voltages is different as they have permanent components that remain throughout the whole dip. There is an increase in the stator and rotor currents that remain throughout the whole dip as shown in Fig. 4, whereas the stator currents reach around 2.09pu. For the most serious phase, and increase in the rotor currents reaches around 1.91pu. Thus, the higher rotor currents lead also to rising DC-link voltage. The peak value of DC-link voltage reaches almost 1298V. Large electrical torque fluctuations occur, the peak value of which around 0.37pu. Also, large fluctuations occur in both the active and reactive power

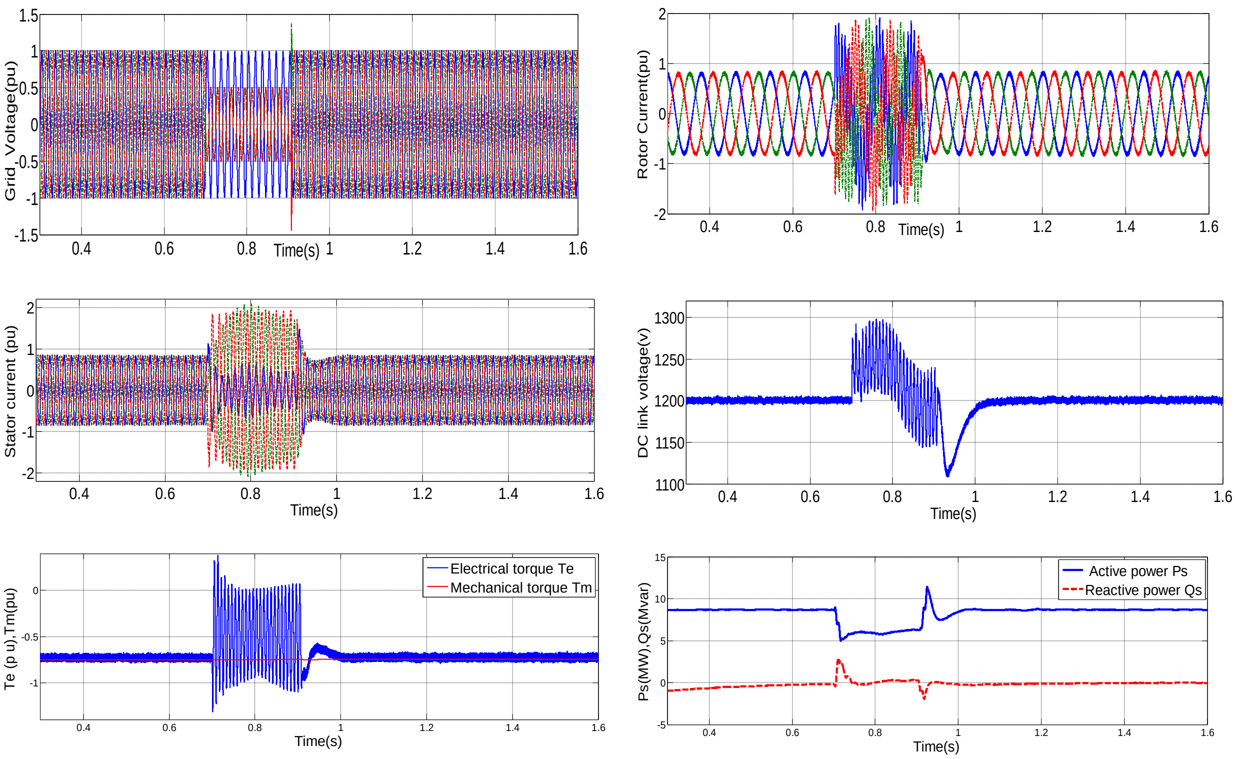


Fig. 4: Phase *b* to *c* short circuit for 0.2

III. Advanced Protection Schemes

This section presents the analysis of the two improved protection schemes for DFIG based wind turbine during symmetrical and asymmetrical voltage dips.

3.1 Series resistor protection scheme

The protection scheme of the series resistor (SR) works in a similar way to the series dynamic braking resistor that has been described in [37]. The series dynamic braking has been used in the stator side of generators. In this protection scheme, the SR consists of a set of resistors that are connected in series with the rotor winding as shown in Fig. 5. It controls the insertion of the resistance inside the rotor circuit by the power electronic switches.

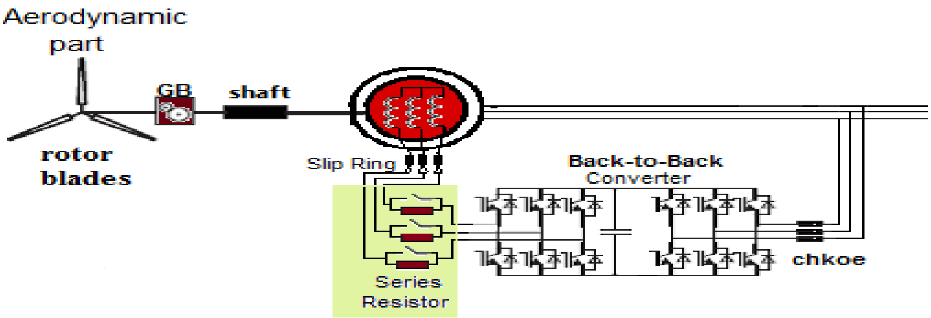


Fig. 5: DFIG based system extended by Series Resistor Protection Scheme

Since the power electronic switch is connected in parallel with the resistance, the switch is on and the resistor is short- circuited in normal operation. During fault conditions, the switch is off throughout the period of the fault and the resistor is connected wholly in series to the rotor winding.

The insertion of the SR inside the rotor circuit during the fault leads to dissipating the power from the induced voltages in the rotor that appears during the fault and hence limits the rotor over current. Limiting the rotor currents reduces the charging current of the DC-link capacitor. This helps avoid DC-link overvoltage.

Due to SR, the high voltage will be shared by the resistance. Because of the series topology, converter control will not be lost. Hence, the SR not only controls the rotor overvoltage which could cause the rotor-side converter to lose control, but also the rotor-side converter does not need to be inhibited during the fault. The SR value in this study is 0.018Ω.

A) Symmetrical fault conditions

Fig. 6 shows the system response to a 0.95pu voltage dip for 0.2s with the series resistance protection scheme. In this simulation, the inclusion of series resistance in the rotor circuit led to dissipate the power from the induced voltages in the rotor appeared during the fault. Thus, the increase in the stator and rotor currents is dampened. The stator currents are decreased from 2.66pu to 2.02pu for the most serious phase. And the rotor currents are decreased from 2.5pu to 1.21pu for the most serious phase. As a result, the DC-link voltage and the electrical torque fluctuations are reduced significantly.

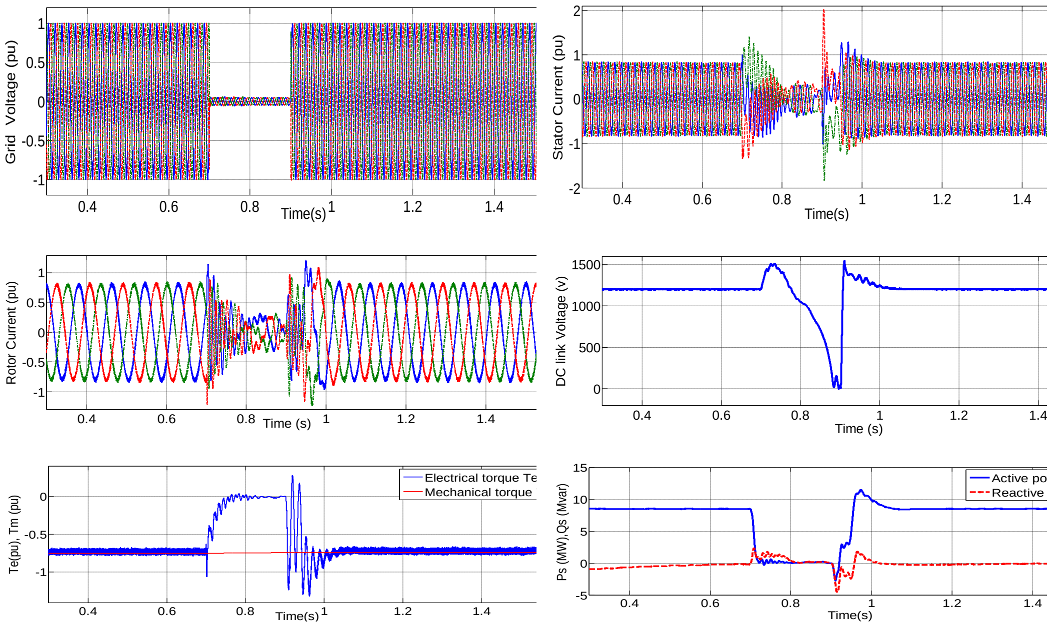


Fig.6: Three-phase 0.95pu voltage dip for 0.2s with Series Resistor protection scheme

B) Asymmetrical fault conditions

Figure 7 shows the system responses during asymmetrical fault conditions. For the phase b to c short-circuited together, the series resistance is effective in terms of dissipating the induced voltage in the rotor. The stator currents decreased from 2.09pu to 1.04pu for the most serious phase. Also, the rotor currents are decreased from 1.91pu to 1.104pu for the most serious phase. Therefore, SR significantly reduces the DC-link voltage and electrical torque fluctuations.

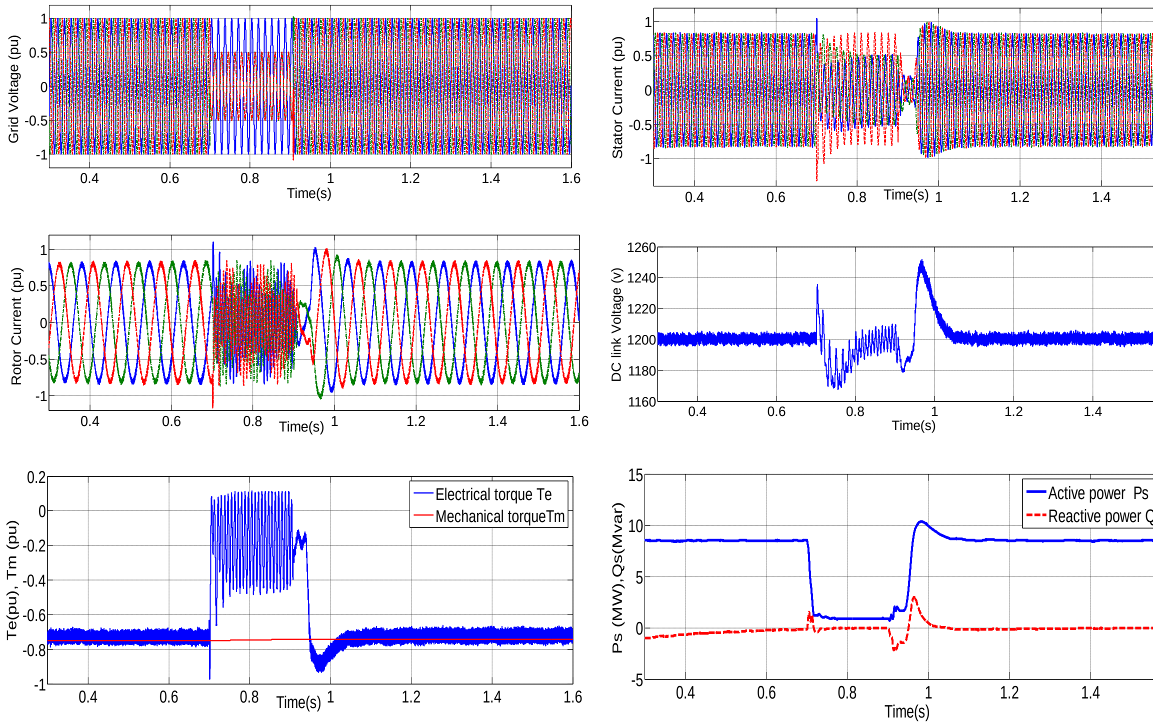


Fig. 7: Phase *b* to *c* short circuit for 0.2s with Series Resistor protection

1.1 Crowbar and DC-chopper protection scheme

The Protection scheme contains two protection circuits: a DC-chopper and crowbar as shown in Fig. 8. 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 (RCB) and DC-chopper (RDCC) are 10kΩ and 11Ω respectively.

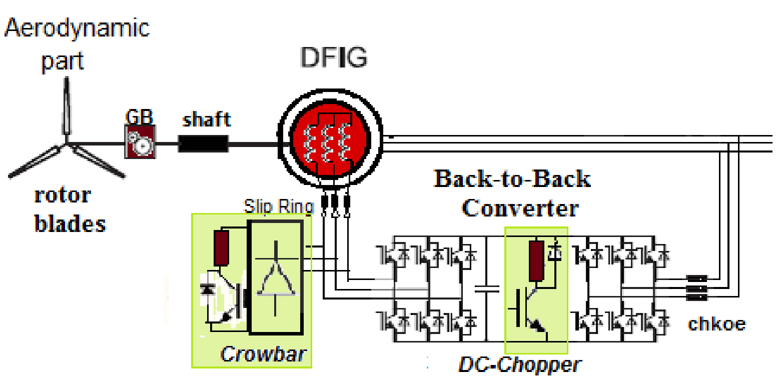


Fig. 8: DFIG based system extended by Crowbar and DC-chopper Protection scheme

A) Symmetrical fault conditions

Figure 9 shows 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.

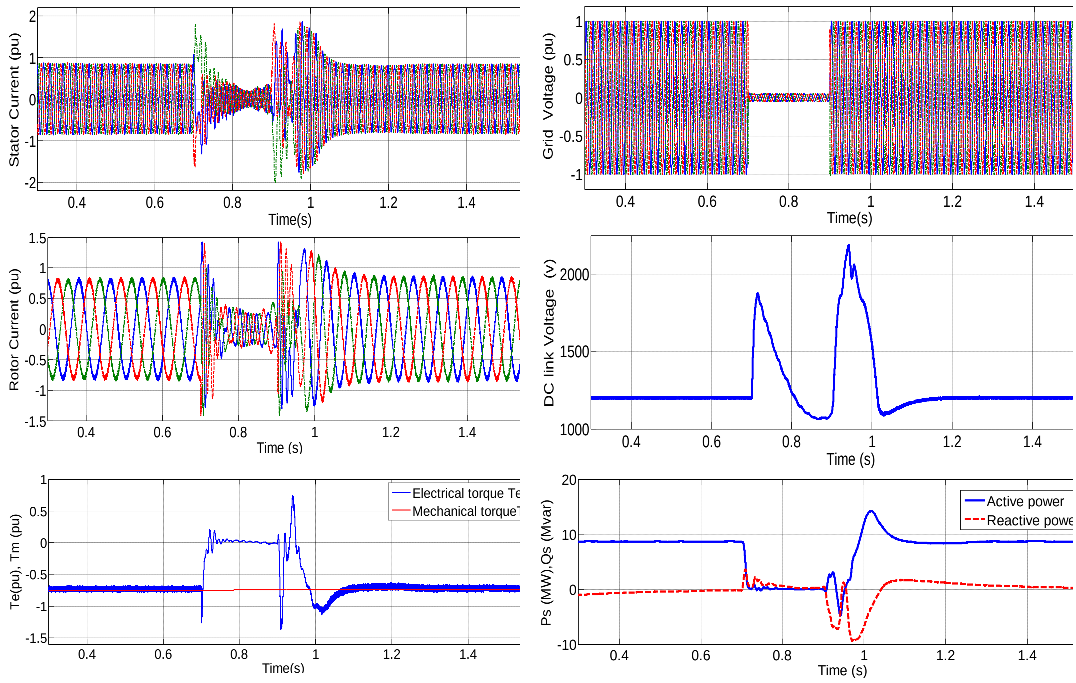
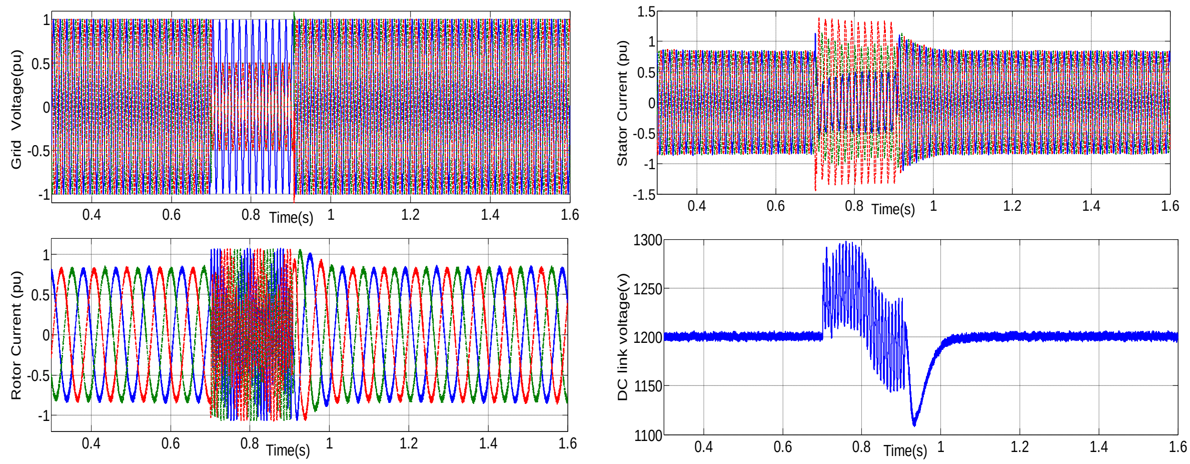


Fig. 9: Three-phase 0.95pu voltage dip for 0.2s with Crowbar and a DC-chopper protection scheme

B) Asymmetrical fault conditions

Figure 10 shows the system responses during asymmetrical 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.



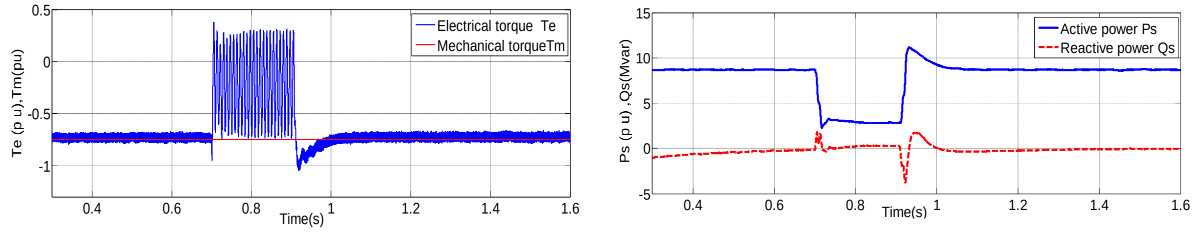


Fig. 10: Phase *b* to *c* short circuit for 0.2s with Crowbar and a DC-chopper protection scheme

IV. Discussion

In this study, the performance analysis of a 1.5MW DFIG-based wind turbine under the symmetrical and asymmetrical grid faults is analyzed for eliminating the negative impacts of the grid faults in the system. From the simulation results, the SR protection is more effective than Crowbar and DC-chopper protection in terms of damping currents increase at the generator terminals. The currents reduction contributes to the stability of the system during the fault occurrence. Therefore, the induced overvoltage will be shared by the resistance. Thus, the power is dissipated within resistance which reduced rotor currents better than Crowbar and DC-chopper protection as illustrated in Table (1). Both of the two strategies have reactive power and electrical torque fluctuations during the fault. However, for crowbar protection, they are much larger. Electrical torque ripple is lower with SR protection compared to crowbar protection.

In addition to that, the SR scheme is based on a simple concept. It decreases the cost and complexity of system. It is useful under symmetrical and asymmetrical grid faults as it decreases the rotor over current, DC-link over voltage and torque oscillations compared to the other scheme. Hence, it contributes to the system stability during the grid faults.

Table (1) Comparison between the SR and Crowbar and DC-chopper protection schemes

		Series resistor protection scheme	Crowbar and DC-chopper protection scheme
Symmetrical faults condition	Stator currents	decreased from 2.66pu to 2.02pu	decrease from 2.66pu to 1.81pu
	Rotor currents	decreased from 2.5pu to 1.21 pu	decreased from 2.5pu to 1.42pu
Asymmetrical fault condition	Stator currents	decreased from 2.09pu to 1.04pu	decreased from 2.09pu to 1.38pu
	Rotor currents	decreased from 1.91pu to 1.104pu	decreased from 1.91pu to 1.06pu

V. Conclusions

The Elimination of the negative impacts of the grid faults in the DFIG based wind turbines systems is investigated in this paper. Two protection schemes are investigated to enhance the DFIGs 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 SR is to avoid the frequent use of Crowbar short-circuit, to maximize the operation time of the RSC, and to reduce the voltage induced in the rotor circuit during the fault occurrence. Though the two protection schemes investigated in this study are effective in protecting the DFIG, it can be concluded that the SR scheme is superior to Crowbar and DC-chopper protection scheme considering the issues of low component cost and better performance.

APPENDIX A

Matlab, version 10, is used in the simulation study. Figure A1 shows the Matlab/Simulink model. The DFIG based wind turbine simulated parameters are given in Table A1.

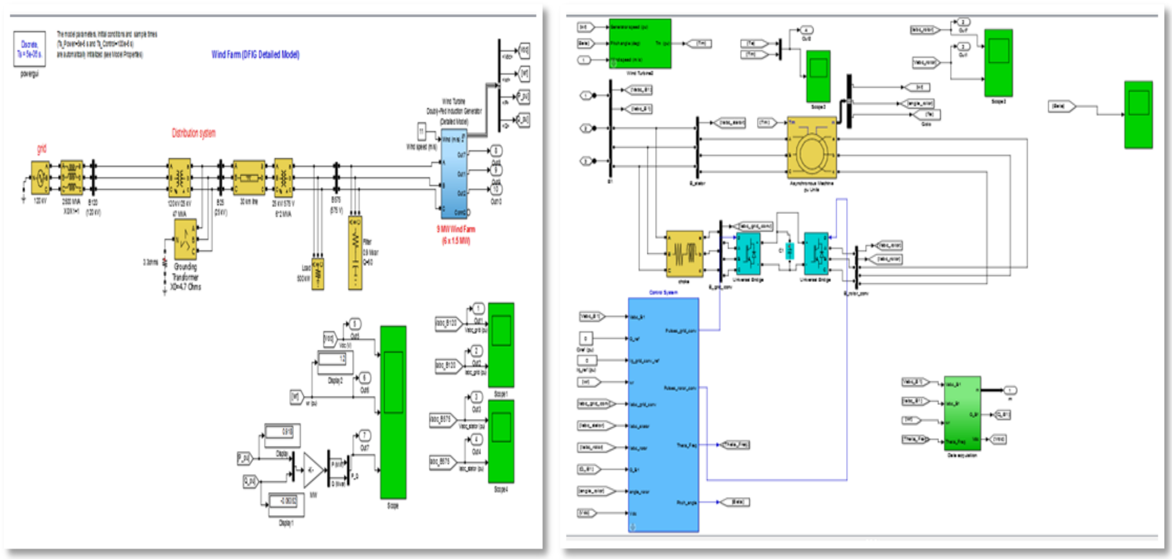


Fig. A1 Matlab/Simulink model of the DFIG based wind turbine

TABEL A1 Simulation parameters of the DFIG and system used in this study

Quantity	Value	*Quantity*	Value
DFIG parameters			
Nominal power	10MVA	Mutual inductance	2.9pu
Nominal voltage (LL)	575V	Inertia constant	5.04s
Nominal frequency	60Hz	Friction factor	0.01pu
Pair of poles	3	Rotor to stator turns' ratio	0.5
Stator resistance and inductance	0.0071, 0.171pu	DC-link capacitance	60mF
Rotor resistance and inductance	0.005, 0.156pu	Filter impedance	0.003+ j0.3pu
Data for each transmission line of the two parallel lines			
Length	30km	Positive- and zero-sequence inductances	1.05, 3.32mH/km
Positive- and zero-sequence resistances	0.1153, 0.413 ohm/km	Positive- and zero-sequence capacitances	11.33, 5.01 nF/km
Transformer T1			
Nominal power	12MVA	Turns ratio	575V /25kV, D/Yg
Nominal frequency	60Hz	Impedance	0.0017+j0.05pu
Transformer T2			
Nominal power	47MVA	Turns ratio	115kV/34.5kV, Yg/D
Nominal frequency	60Hz	Impedance	0.00534+j0.16pu
Grid impedance			
Impedance	0.0004+j0.004pu		

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