Application of STATCOM and CROWBAR for Transient Stability Improvement and Performance Enhancement for A Wind Turbine based Doubly Fed Induction Generator

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Abstract: This paper presents a robust control of Doubly Fed Induction Generator (DFIG) wind turbine in a sample power system. DFIG consists of a common induction generator with slip ring and a partial scale power electronic converter. Indirect field-oriented controller is applied to rotor side converter for active power control and voltage regulation of wind turbine. On grid side PQ control scheme is applied. Wind turbine and its control units are described in details and also for STATCOM control. All power system components are simulated in MATLAB/ SIMULINK software. For studying the performance of controller, different abnormal conditions are applied even the worst case. Simulation results prove that the performance of STATCOM and DFIG control schemes as improving power quality and stability of wind turbine.

Keywords: STATCOM, PQ control theory, induction machine, PWM, crowbar, rotor side controller, grid side controller, DFIG, wind turbine.

I. INTRODUCTION

To have sustainable growth and social progress, it is necessary to meet the energy need by utilizing the renewable energy resources like wind, biomass, hydro, co-generation, etc. In sustainable energy system, energy conservation and the use of renewable source are the key paradigm. The need to integrate the renewable energy like wind energy into power system is to make it possible to minimize the environmental impact on conventional plant [1]. The integration of wind energy into existing power system presents a technical challenges and that requires consideration of voltage regulation, stability, power quality problems. The power quality is an essential customer-focused measure and is greatly affected by the operation of a distribution and transmission network. The issue of power quality is of great importance to the wind turbine [2].

There has been an extensive growth and quick development in the exploitation of wind energy in recent years. The individual units can be of large capacity up to 2 MW, feeding into distribution network, particularly with customers connected in close proximity [3]. Today, more than 28000 wind generating turbine plants are successfully operating all over the world [6, 9]. In the fixed-speed wind turbine operation, all the fluctuation in the wind speed are transmitted as fluctuations in the mechanical torque, electrical power on the grid and leads to large voltage fluctuations. During the normal operation, wind turbine produces a continuous variable output power. These power variations are mainly caused by the effect of turbulence, wind shear, and tower-shadow and of control system in the power system. There has to be a protection for such situations [4]. Thus, the network needs to manage for such fluctuations. The power quality issues can be viewed with respect to the wind generation, transmission and distribution network, such as voltage sag, swells, flickers [8], harmonics etc. However the wind generator introduces disturbances into the distribution network.

One of the simple methods of running a wind generating system is to use the induction generator connected directly to the grid system [5]. The proposed STATCOM control scheme for grid connected wind energy generation for power quality improvement has following objectives.

- Unity power factor at the source side.
- Reactive power support only from STATCOM to wind Generator and Load.
- Simple bang-bang controller for STATCOM to achieve fast dynamic response.

Shunt Flexible AC Transmission System (FACTS) devices, such as the Static Var Compensator (SVC) and the Static Synchronous Compensator (STATCOM), have been widely used to provide high performance steady state and transient voltage control at the Point of Common Coupling (PCC) [6]. The applications of a SVC or a STATCOM to fixed-speed wind turbines equipped with induction generators have been reported in [7] for steady state voltage regulation, and in [1] for short-term transient voltage stability. Doubly fed induction generator (DFIG) is one of the most popular wind turbines which includes an induction generator with slip ring, a partial scale power electronic converter and a common DC-link capacitor.

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Power electronic converter which encompasses a back to back AC-DC-AC voltage source converter has two main parts; grid side converter (GSC) that rectifies grid voltage and rotor side converter (RSC) which feeds rotor circuit. Power converter only processes slip power therefore it's designed in partial scale and just about 30% of generator rated power [13] which makes it attractive from economical point of view.

The paper is organized as fallows. The Section II introduces the wind turbine model. The Section III introduces STATCOM controller and overall system design in MATLAB. The Section IV describes the topology for power quality improvement. The Sections V, VI, VII describes the result analysis, conclusions and references respectively.

II. WIND TURBINE MODEL

The aerodynamic model of a wind turbine can be characterized by the well-known CP-λ-β curves. CP is called power coefficient, which is a function of both tip-speed-ratio λ and the blade pitch angle β. The tip-speed-ratio λ is defined by

$$\Lambda = \omega_t R / v_w \quad (1)$$

where R is the blade length in m, ωt is the wind turbine rotor speed in rad/s, and vw is the wind speed in m/s. The CP-λ-β curves depend on the blade design and are given by the wind turbine manufacturer. Given the power coefficient CP, the mechanical power extracted by the turbine from the wind, is calculated by [1], [8]

$$P_m = \frac{1}{2}\rho A_r v_w^3 C_P(\lambda, \beta) \quad (2)$$

where ρ is the air density in kg/m^3; Ar = πR2 is the area in m2 swept by the rotor blades. At a specific wind speed, there is a unique value of ωt to achieve the maximum power coefficient CP and thereby extract the maximum mechanical (wind) power. If the wind speed is below the rated (maximum) value, the wind turbine operates in the variable speed mode, and the rotational speed is adjusted (by means of active power control in the DFIG) such that the maximum value of CP is achieved. In this operating mode, the wind turbine pitch control is deactivated and the pitch angle β is fixed at 0○. If the wind speed is above the rated value, the rotor speed can no longer be controlled within the limits by increasing the generated power, as this would lead to overloading of the generator and/or the converter. In this situation, the pitch control is activated to increase the wind turbine pitch angle to reduce the mechanical power extracted from wind. Figure 5 shows the structure of the pitch angle controller [1], [8]. Pt (= Ps + Pr) is the total output active power from the induction generator.

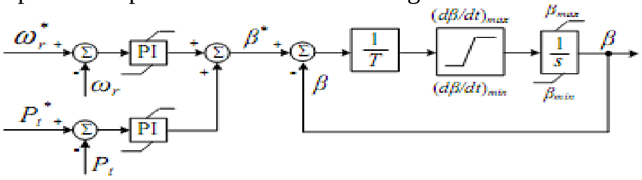

Fig. 1. Wind turbine pitch angle controller

III. DFIG ROTOR AND GRID CONTROL SCHEMES AND STATCOM MODEL

A STATCOM [6], [12], also known as an advanced static VAR compensator, is a shunt connected FACTS device. It generates a set of balanced three-phase sinusoidal voltages at the fundamental frequency, with rapidly controllable amplitude and phase angle. A typical application of a STATCOM is for voltage support. In this paper, the STATCOM is modeled as a IGBT PWM converter with a dc-link capacitor. The objective of the STATCOM is to regulate the voltage at the PCC rapidly in the desired range and keep its dc-link voltage constant. It can enhance the capability of the wind turbine to ride through transient disturbances in the grid. The overall control scheme of the STATCOM is shown in Fig. 2.

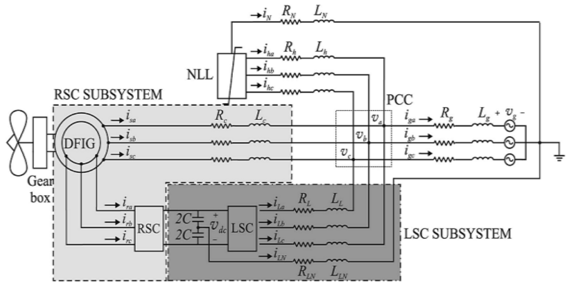

Fig. 2. System configuration: the DFIG stator is connected to the PCC; DFIG rotor is supplied by two back-to-back connected converters; the dc-link central tapis tied to the neutral. NLL is connected to the PCC. The step-up transformer and the supply line are represented by means of their Thevenin equivalent.

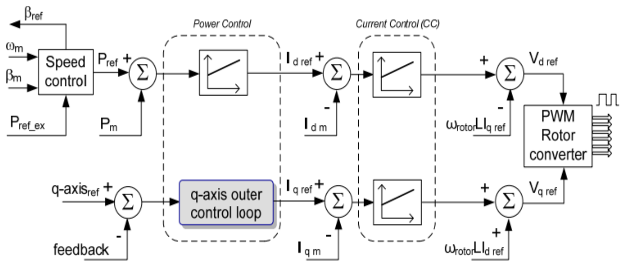

Fig 3. Control scheme for Rotor side controller

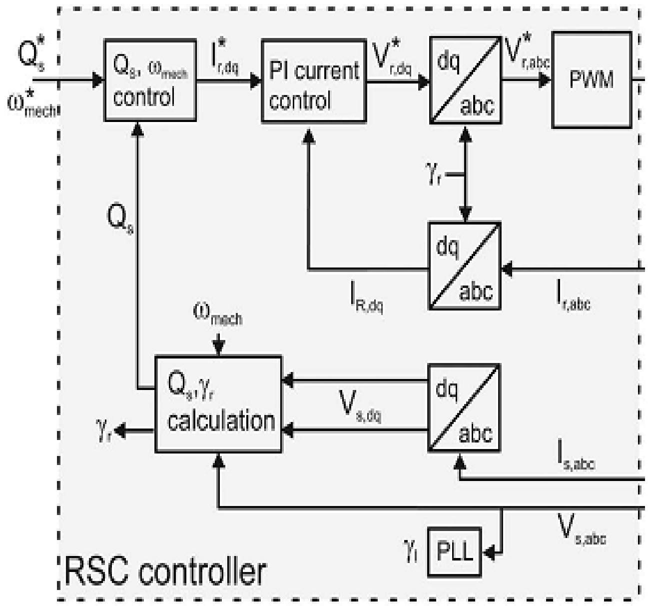

Fig 4. Control scheme for Grid side controller

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The reference d-axis current, which is formed by PI controller and q-axis current, which set to zero are both transformed to abc reference frame using the Park's transformation inverse.

The error signals issued from the comparison between current reference values and actual ones are applied to PWM controllers. The logical outputs of these controllers are the switching signals of power transistor in GSC to maintain the desired currents. The proposed scheme is shown in fig. 3.

The Grid side controller (GSC) controls the dc voltage Vdc and provides reactive power support. which is used to design the outer dc voltage control loop, where Cdc is the dc capacitance and Idc and Iload are the dc currents on LSC and RSC side, respectively. A voltage-oriented cascade vector control structure with inner current control loops is applied. The line current Il can be controlled by adjusting the voltage drop across the line inductance as shown in Fig4.

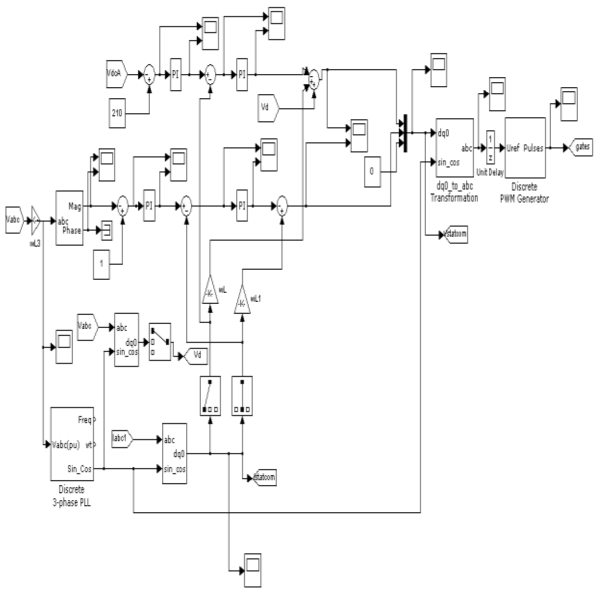

Fig 5. Control scheme for STATCOM

In its most basic form, the STATCOM configuration consists of a VSC, a dc energy storage device; a coupling transformer connected in shunt with the ac system, and associated control circuits. Fig.5, shows the basic configuration of STATCOM with wind turbine driven DFIG connected directly to the grid. The VSC converts the dc voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and coupled with the ac system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the STATCOM output voltages allows effective control of active and reactive power exchanges between the STATCOM and the ac system.

The VSC connected in shunt with the ac system provides a multifunctional topology which can be used for up to three quite distinct purposes:

1) Voltage regulation and compensation of reactive power
2) Correction of power factor
3) Elimination of current harmonics.

The design approach of the control system determines the priorities and functions developed in this analysis. In this paper, the STATCOM is used to regulate voltage at the point of connection. The control is based on discrete PWM and only requires the measurement of the rms voltage at the load point, reference voltage near the grid and dc voltage near the STATCOM VSC converter.

IV. DESIGN OF DFIG SYSTEM WITH RSC, GSC AND STATCOM

The wind energy generating system is connected with grid having normal and non-linear load. The performance of the system is measured by switching the STATCOM at time s in the system and how the STATCOM responds to the step change command for increase in additional load at 1.0s is shown in the simulation. When STATCOM controller is made ON, without change in any other load condition parameters, it starts to mitigate for reactive demand as well as harmonic current. The dynamic performance is also carried out by step change in a load, when applied at 1.0 s. This additional demand is fulfill by STATCOM compensator. Thus, STATCOM can regulate the available real power from source.

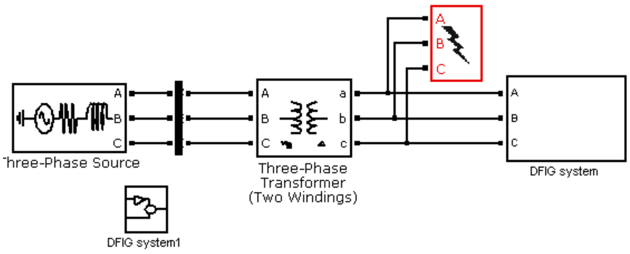

Fig 6a. Overall system design for wind turbine driven DFIG and STATCOM controller

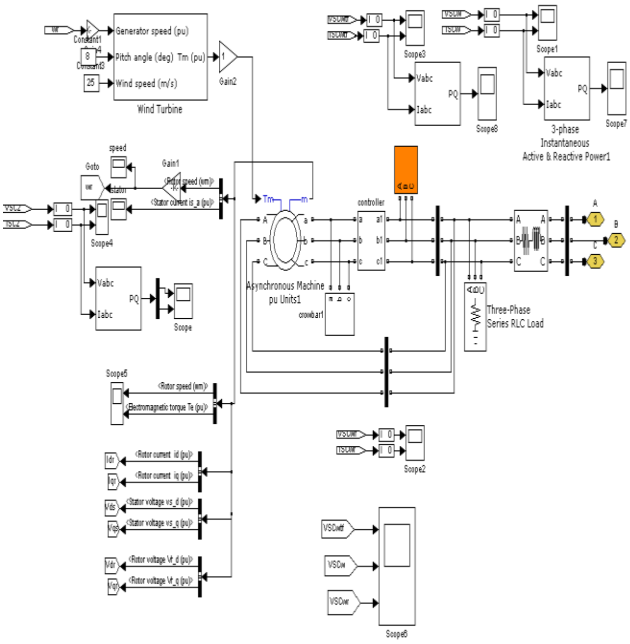

Fig 6b. Internal block diagram of DFIG, crowbar protection and STATCOM controller

V. UNINTERRUPTED OPERATION FEATURE OF THE WIND TURBINE DURING GRID FAULTS

The idea behind this feature is that the wind turbine does not trip when the when a severe symmetrical fault occurs near the grid or near the generator system. The wind turbine continues its operation with the induction generator (IG) with a short-circuited rotor circuit, such that the speed of the IG decreases. It may sometimes reach zero when a low impedance short circuit occurs.

During such an operation condition, the self controllability of the IG is naturally lost and there is no longer any independent control of active and reactive power in the DFIG. The generator becomes a conventional induction generator, which produces an amount of active power and starts to absorb an amount of reactive power. In order to prevent the wind turbine from over-speeding or under speeding, the pitch angle controller can be activated to keep the speed around the pre-defined value.

During such circumstances, the STATCOM control system continues monitoring the generator current, the terminal voltage, the active and reactive powers and the generator rotor speed. When the fault has cleared and when the terminal voltage and the rotor current return back to their pre-defined ranges, the STATCOM starts synchronization [1]. At synchronization, the STATCOM starts switching and the external resistance is disconnected; the d-q components of the STATCOM voltage source (Fig. 2) are set to vdr = idr· Rext and vqr = iqr· Rext, which are used by the PWM module to generate the IGBT gate control signals to drive the IGBT converter. When the synchronization seems to be complete, the control system of the STATCOM switches to the regular control system as shown in Fig. 3 and the STATCOM re-starts. When the STATCOM has re-started, the SCIG again has independent active and reactive power control and the wind turbine returns to normal operation.

The advantages of this uninterrupted operation feature include: (1) the wind turbine continues supplying the active power to the power network and therefore the demand for immediate power reserves does not exist or it is reduced; (2) the wind turbine can contribute to maintaining the frequency in the power network during a transient state.

The controllability of RSC, GSC and STATCOM are analyzed in deep in this work. The rotor current controller should only regulate the positive sequence component of the rotor currents. The severe voltage disturbance introduced by the derivative of the stator flux should be feed-forward compensated at the beginning and at the end of the fault, for a short duration, so that rotor current control can be maintained

In the case of a weak power network, there can be a risk of voltage instability initiated by the grid fault. As a result, the STATCOM will not re-start and the wind turbine will be disconnected from the network. But STATCOM is to used as dynamic reactive compensator – to provide transient voltage support to help the wind turbine IG ride through grid faults. In addition, the STATCOM can also be used for steady state voltage regulation and power factor control of the SCIG.

VI. RESULT ANALYSIS

The system design is as shown in Fig 3. It is wind turbine driving induction machine as generator and STATCOM is connected near the midpoint of the system. In this analysis, there are three cases, first is without Gris Side Controller (GSC), Rotor Side Controller RSC and STACOM and with symmetrical fault near PCC, and second is with without STACOM, but with GSC and RSC having the same disturbance as in previous case and in third case, with GSC, RSC and with STATCOM with same three phase to ground fault occurring in the system. The system performances in all the cases are observed when a severe symmetrical short circuit occurs in the system with fault resistance of 0.1 ohms were considered.

Case 1: without GSC, RSC and STACOM with three phases to ground fault at PCC

A symmetrical fault occurred at 0.1s and cleared at 0.15s for the system without GSC, RSC and STATCOM but with crowbar controller. The crowbar controller is designed with hysteresis scheme, with variable current flow control by using a resistance and IGBT connected in series to each other and crowbar is connected in parallel and placed near the rotor of DFIG.

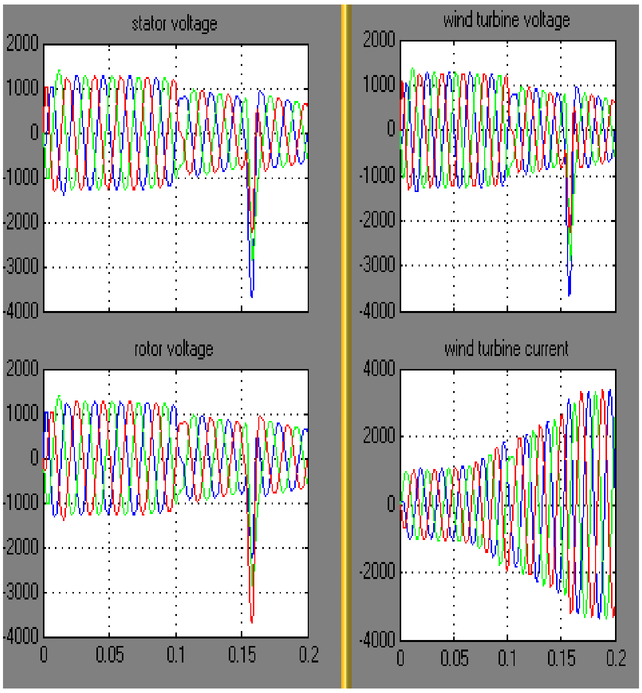

Fig 7. Without STACOM (left side) and with STACOM (right side) showing speed, torque and current waveforms in pu.

A 3phase to ground fault occurred near PCC at 0.1s and cleared at 0.15s is as shown in Fig 7. It can be observed that, the voltage and current slowly decreasing due to this disturbance. At the moment of fault clearance, a severe surge is produced and the output voltage of DFIG is decreasing and current is increasing.

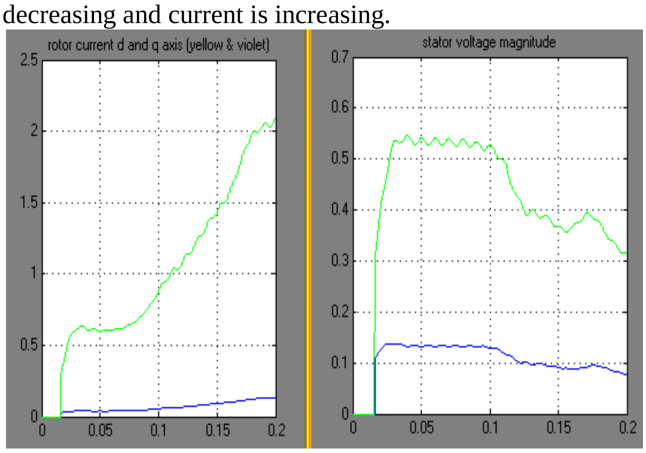

Fig 8. The d-q axis rotor current (left) and stator voltages (right)

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The Fig 8 depicts that the direct and quadrature axis current of rotor and stator voltages are highly unstable and starts to violate theirlimits leading to severe unstable operation of the system

Case 2: with GSC, RSC and without STACOM and with three phase to ground fault in the system

Although occurrence of three Ph-G faults is very low practically, such fault leads to destruction in system and system collapse. When a symmetrical fault occurs between 0.1s to 0.15s, the system results are verified without STATCOM but with GSC and RSC schemes.the control schemes are shown in Fig 3 and 4.

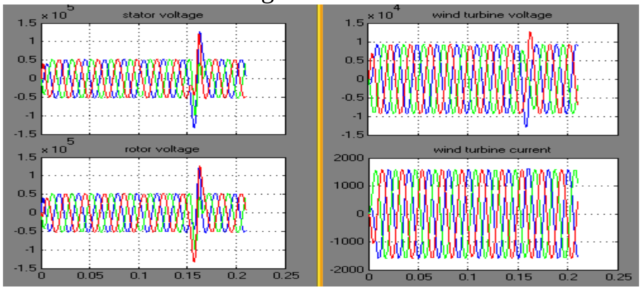

Fig 9. With GSC and RSC but without STACOM showing voltage and current waveforms i with a 3PHG fault between 0.1 to 0.15s

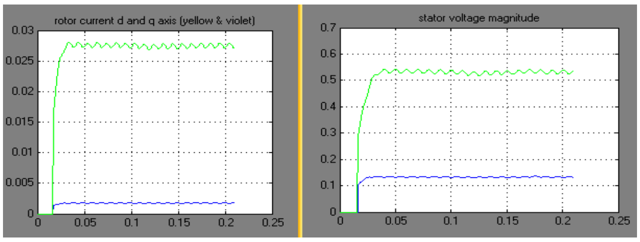

Fig 10. The d-q axis rotor current (left) and stator voltages (right) with GSC and RSC schemes

During this scenario, a three phase to ground fault with fault resistance of 0.1 ohms occurs between phases at 0.1seconds and cleared at 0.15s. The stator and rotor voltages and currents are nearly maintained before and after the fault in this case. In Fig 9, it can be observed that stator and rotor voltages and current are same at pre-fault and post fault, but there is a surge current produced after clearing of fault. In fig 10, direct and quadrature axis current of rotor and voltage of stator are nearly maintained constant, due to the absorption of fault current by RSC.

Case 3: with STACOM and with three phase to ground fault in the system

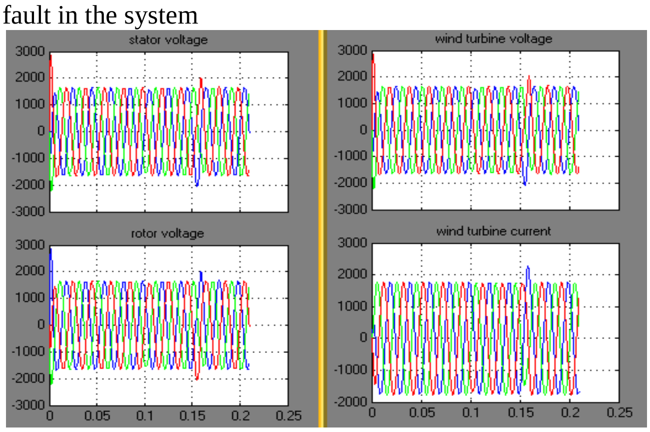

Fig 11. With GSC, RSC and STACOM showing voltage and current waveforms with a 3PHG fault between 0.1 to 0.15s

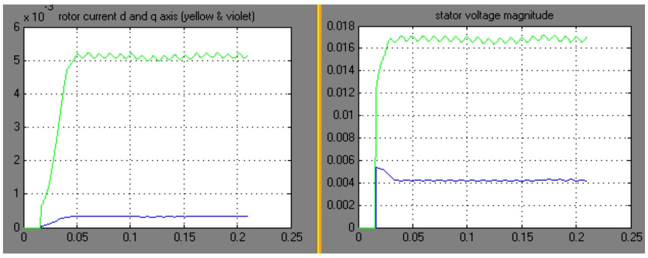

Fig 12. The d-q axis rotor current (left) and stator voltages (right) with GSC and RSC schemes

In this case as shown in Fig 11, the voltages and currents of stator and rotor are same at pre-fault, during and also at post fault conditions. The surge currents and voltages at stator side are also limited by the STATCOM. Hence overall system performance has improved by incorporating sophisticated RSC, GSC and STATCOM control schemes. The dq axis voltages and currents of stator and rotor are also maintained constant in this case. In this case, not only stability improved, reactive power generation has controlled and real power transfer has increased. The overall system power factor delivering to grid improved.

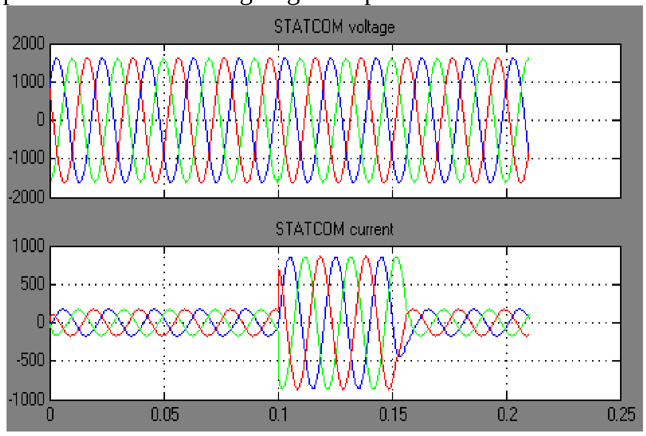

Fig13. Showing injected three phase voltage and current by STATCOM

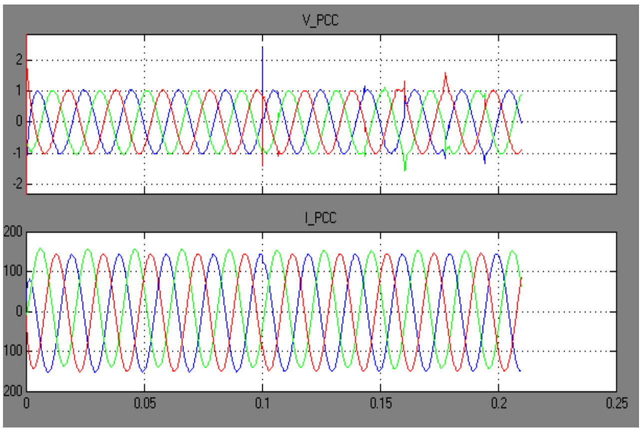

Fig15. Output voltage and current from wind turbine system reaching PCC

The system with GSC, RSC and STATCOM controller with a three phase to ground fault occurs between 0.1s to 0.15s are shown in figures 11 to 15. If comparing without and with STATCOM from Fig 9 and 11, the voltage and current ripples near stator has minimized. The excess short circuit current flowing through the rotor of DFIG is diverted through STATCOM by using dual flow voltage regulator control scheme.

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In fig 14, it can be observed that severe surge current is entering into STATCOM, charging the capacitor making it as lagging compensation. After fault clearance again, the voltage and current of STATCOM reached to its normal value, thereby changing its power factor again. Hence STATCOM is current injected VSC with power factor correction

VII. CONCLUSIONS

With a sophisticated controller for GSC, RSC and STATCOM, there can be high improvement in overall power system stability, reactive power flow, extraction of maximum power from DFIG, maintaining nearly constant voltage at PCC even after occurrence of severe symmetrical fault anywhere in the system. It is desired to protect the system from surge currents and harmonics mitigation and flickering issues. It can also be observed that stability of system enhanced, reactive power flow has been controlled. The STATCOM based controller not only control current from stator and rotor or improves stability, it can mitigate both current and voltage harmonics occurring in the system..

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