

Voltage Control of Wind Farm Base on FSIG Using Static Synchronous Compensator

Giddani Kalcon, Abdelaziz Y. M. Abbas, Aamir Hashim Obeid

Abstract— Static synchronous compensator (STATCOM) is used to improve the voltage stability and fault ride through capability of wind farm based on fixed speed induction generator. The STATCOM uses PWM technique to control the switching of STATCOM switching devices with high frequency of 2 KHz. The robustness of STATCOM control system is investigated during state steady state and transient conditions including wind power variation and symmetrical fault at point of common coupling (PCC). The overall study is carried-out using SIMULINK environment.

Index Terms— FSIG, Reactive Power Control, SATCOM, and VSC

NOMENCLATURE

FSIG	Fixed speed induction generator
FACT	Flexible transmission system
VSC	Voltage source converter
STATCOM	Static synchronous generator
PCC	Point of common coupling
DFIG	Doubly-fed induction generator

I. INTRODUCTION

The global governments targets to reduce the CO₂ emissions, requires the installation of new large generation units based on renewable sources. The majority of this power is expected to come from wind located in remote areas (onshore/offshore) and often at considerable distance from the existing transmission system. At the present the two established wind technologies are fixed and variable speed wind turbines. Fixed speed induction generators wind turbines (FSIGs) are simple, robust, and well proven technology for wind power generation. These wind turbines generators are directly coupled to the grid. The main disadvantage of this technology is that the wind turbine rotor speed is fixed regardless of the wind speed, and this does not allow maximum power extraction. Also the fixed speed wind turbine generators required reactive power therefore couldn't control their terminal voltage. Variable speed wind turbine generators allow maximum power extraction and inherent reactive power capability at no additional cost. Furthermore, they can absorb any fluctuations in the generated power and voltage come from the intermittency nature of wind, therefore no flickers are generated and they can meet most of the current grid codes [1-3].

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In the past wind farms connected to power networks were small-size capacity and the penetration of wind power was small compared with the total installed generation. There were no special requirements for wind farm integration to the network because their impact on power system network stability was very small and could be neglected. Nowadays, the situation has changed due to the dramatic increase on installed wind power. An increase in wind power penetration means that wind power plants have considerable impact on system stability, and they must satisfied special requirement before connection to power system. Many countries such as Denmark, Germany, Spain, and UK have issued new connection codes for wind farms connection. The new requirements state that wind farms must provide additional functionality, such as [4-5]

- Wind farms are required to be capable to regulate the reactive power to control the voltage at PCC.
- A wind farm must be able to operate with constant active power output for system frequency within 49.5Hz and 50.5 Hz
- A wind farm must remain transiently stable for solid short-circuit with duration of 140ms and meet fault ride through capability.

The uses of STATCOM with fixed speed wind farm add functionalities to wind farm in order to meet the grid code requirements. In this case the STATCOM replace the conventional reactive compensation devices such as synchronous condenser and capacitor bank and provide continuous voltage support at PCC. Also STATCOM based on PWM voltage source converters normally have better dynamic performance during ac network faults and enhance the FSIG to remain connected during system disturbances.

In recent years, the use of STATCOM to assist large wind farm integration or to reinforce long distance transmission line becomes a common practice. The authors in [6] present a coordinated voltage control scheme for improving the network voltage profile and for minimizing the steady-state loading of the STATCOM to effectively support the system during contingencies. The paper addresses implementation issues associated with primary voltage control and optimal tracking secondary voltage control for wind parks based on self-excited induction generators which comprise STATCOM and under-load tap changer (ULTC) substation transformers. The voltage controllers for the STATCOM and ULTC transformer are coordinated and ensure the voltage support. Also the authors in [7] investigate the problem of voltage compensation by reactive current injection, at the end of a distribution line. A dynamic model of the system is analytically derived and a linear controller designed, based on the derived model. Frequency domain analysis is performed

on the compensated system and experimental results obtained to validate the analytical predictions. In this paper the uses of STATCOM for voltage control in network with wind power penetration and long distance transmission line is investigated during several operational conditions.

II. PULSE WIDTH MODULATION STATCOM

As seen in Fig.1, the STATCOM is built using two or multi level voltage source converter (VSC) which employ semiconductor switching devices which can be switched ON and OFF at any time such as IGBT, GTO. The converter is connected to DC side including DC capacitor act as storage device. The STATCOM is connected to AC side through interfacing reactor.

The inherent capability of VSC to generate or absorb reactive power can be used to control the ac voltage of the network at point of common coupling (PCC). In this case the VSC acts as a static reactive power compensator with instantaneous response because the VSC has no inertia. The ac current and voltage of the VSC can have any phase relationship, and the converter can act as a rectifier or an inverter with leading or lagging reactive power. The STATCOM is used to regulate the reactive power at PCC by injecting quadrature lagging or leading current with system voltage. In this case the STATCOM acts as reactor to absorb the reactive power or capacitor to generator the reactive power.

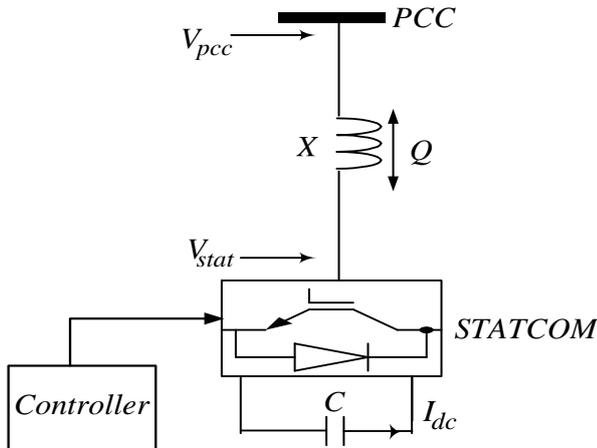


Fig. 1: STATCOM connection

The reactive power exchange between the STATCOM and PCC is controlled by regulating the STATCOM voltage (v_{stat}) according to the following equation [8-9]:

$$Q = \frac{3v_{stat} * v_{pcc} \cos(\delta)}{X} - \frac{V_{stat}^2}{X} \tag{1}$$

Where V_{stat} is STATCOM fundamental output AC phase voltage (rms), V_{pcc} is fundamental output AC phase voltage (rms) at PCC, X is the leakage reactance of interfacing reactor, and δ is the phase angle between V_{pcc} and V_{stat} . If the magnitude of STATCOM voltage is bigger than the voltage at PCC than the STATCOM inject capacitive reactive power into the system. If the magnitude of STATCOM voltage is smaller than the voltage at PCC than the STATCOM absorb inductive reactive power from the system.

In this case the control of STATCOM voltage is achieved using high frequency PWM technique. The relation between the STATCOM DC side voltage and STATCOM AC side voltage is

$$v_{stat} = M \frac{V_{dc}}{2} \sin(\omega t) \tag{2}$$

where M is the modulation index, V_{dc} the dc voltage, ω is the system frequency. The VSC controller system is used to maintain the dc voltage and adjust the variable M to increase or decrease the STATCOM voltage magnitude and hence, control the active and reactive power flows.

III. STEM LAY-OUT

Fig. 1 shows a schematic diagram of STATCOM based on voltage source converter connected to a 200MW, 33kV offshore wind farm based on fixed speed asynchronous generator through a 13.8kV/33kV transformer. The point of common coupling with offshore substation (B_1) is located 150km from onshore substation bus (B_2). Loads connected to bus B_2 are (340+j130) MVA. The STATCOM is controlled using carrier-based sinusoidal PWM with 2.1 kHz switching frequency. Table I summarizes the test system parameters.

Table II: Parameters of the test system used in simulation

STATCOM rating	100MVA	k_{pdc}	0.0015
DC link voltage	28.7kV	k_{ide}	1.2
DC link capacitance	5mF	k_{pi}	3
Interfacing transformer impedance in per unit	0.004+j0.64	k_{ii}	300
Switching frequency	2.1kHz	k_{pac}	0.0015
Modulation strategy	SPWM	k_{iac}	200

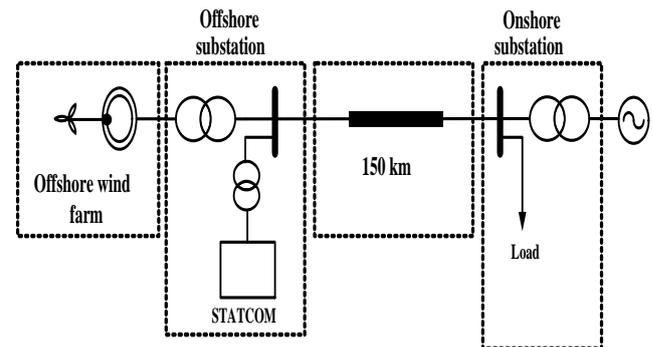


Fig. 2: Test system.

IV. STATCOM DYNAMIC MODEL

The mathematical model of STATCOM in open literature based on the dq reference frame [10-12] is:

$$L \begin{bmatrix} \frac{di_{sd}}{dt} \\ \frac{di_{sq}}{dt} \end{bmatrix} = \begin{bmatrix} v_{dpcc} - v_{dstat} \\ v_{dpcc} - v_{dstat} \end{bmatrix} + \begin{bmatrix} -R & \omega L \\ -\omega L i_q & -R \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} \tag{3}$$

where R and L are the parameter of coupling reactor and interfacing transformer.

In a converter with sinusoidal PWM the relationship between the modulation index M, DC link voltage, load angle of STATCOM AC voltage and the dq components of the AC voltage are given by:

$$\begin{bmatrix} v_{dstat} \\ v_{qstat} \end{bmatrix} = V_{dc} \frac{M}{2} \begin{bmatrix} \cos \delta \\ \sin \delta \end{bmatrix} \quad (4)$$

In order to design an inner current controller the cross coupling terms in equations (1) and (2) are decoupled as follow:

$$\begin{bmatrix} v_{dpcc} \\ v_{qpcc} \end{bmatrix} = \begin{bmatrix} u_d \\ u_q \end{bmatrix} + \begin{bmatrix} 0 & -\omega L \\ \omega L i_q & 0 \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} v_{dstat} \\ v_{qstat} \end{bmatrix} \quad (5)$$

Where the new variable are defined as follow

$$u_d = Ri_{sd} + L \frac{di_{sd}}{dt} = k_{pi}(i_{sd}^* - i_{sd}) + k_{ii} \int (i_{sd}^* - i_{sd}) dt \quad (6)$$

$$u_q = Ri_{sq} + L \frac{di_{sq}}{dt} = k_{pi}(i_{sq}^* - i_{sq}) + k_{ii} \int (i_{sq}^* - i_{sq}) dt \quad (7)$$

where k_{pi} and k_{ii} are the proportional and integral gains of the current controller which regulates the current and restrains its value during network disturbances to prevent the STATCOM components from experiencing high current stresses that may lead to their destruction. The references values (i_{sd}^* & i_{sq}^*) are obtained using outer loops controller.

The main controllers of the STATCOM used in this paper are the dc voltage controller that regulates the DC link voltage at 28.7Kv and AC voltage controller that controls the ac voltage of the bus B_{PCC} at 1.0 per unit. The reference currents for the inner controller as follow:

$$i_{sd}^* = k_{pdc}(V_{dc}^* - V_{dc}) + k_{idc} \int (V_{dc}^* - V_{dc}) dt \quad (8)$$

$$i_{sq}^* = k_{pac}(V_{pcc}^* - V_{pcc}) + k_{iac} \int (V_{pcc}^* - V_{pcc}) dt \quad (9)$$

where k_{pdc} and k_{idc} are the proportional and integral gains of the DC voltage controller and k_{pac} and k_{iac} are the proportional and integral gains of the AC voltage controller.

The inner current loop for STATCOM is designed according to equations (8 and 9). The gains of the current controller are selected such that the closed loop system must reach steady state after $5\tau_i$, where τ_i is the closed loop time constant [5]. The block diagram of this current control is shown in Fig. 4 and the Laplace transfer function is given by:

$$\frac{i_d(s)}{u_d(s)} = \frac{i_q(s)}{u_q(s)} = \frac{1}{R + sL} \quad (10)$$

$$G(s) = \frac{i_d(s)}{i_d^*(s)} = \frac{i_q(s)}{i_q^*(s)} = \frac{\frac{1}{(R + sL)} \times \frac{(k_{pi}s + k_{ii})}{s}}{1 + \frac{1}{(R + sL)} \times \frac{(k_{pi}s + k_{ii})}{s}} \quad (11)$$

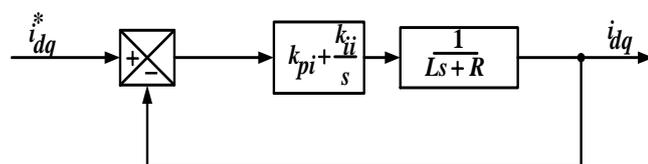


Fig. 3. Block diagram of the current control loop

The transfer function in equation (8) can be reduced to first order as in (9) using pole cancellation.

$$G(s) = \frac{1}{\tau_i s + 1} \quad (12)$$

The current controller proportional and integral gains of the inner (current) controller are related to the closed loop time constant as follow:

$$k_{pi} = \frac{L}{\tau_i} \quad (13)$$

$$k_{ii} = \frac{R}{\tau_i} \quad (14)$$

The block diagram of the complete control system is shown in Fig. 2. As the STATCOM only draws a small amount of active power from the ac network to maintain its DC link voltage (plus losses), the feed-forward term of the dc voltage control is considerably small and can be neglected as shown in Fig. 2.

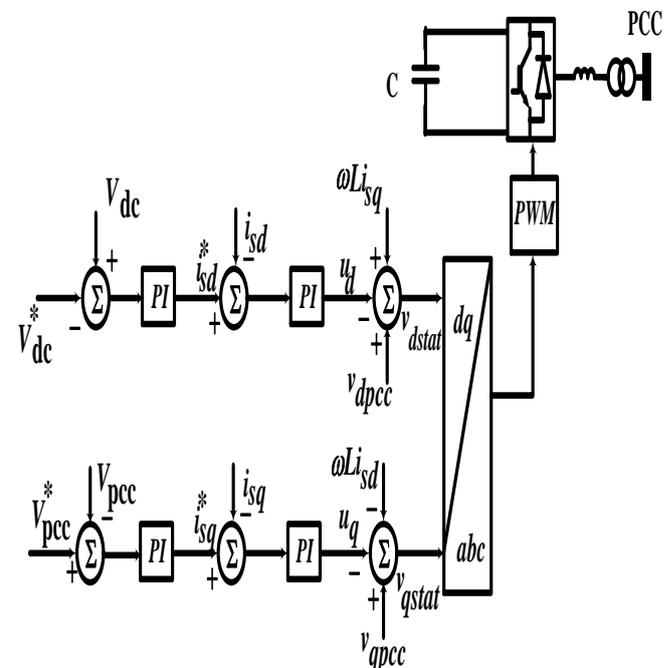


Fig. 4: STATCOM control system block diagram

V. FSIG DYNAMIC MODEL

Fixed-speed wind turbines use a squirrel-cage induction generator to convert the mechanical power to electrical power. The dynamic model of induction generator and mechanical system used in this paper is found in [13-14]. The wind turbine rotor transforms the absorbed kinetic energy of the air into mechanical power. The mechanical produced by the wind turbine is expressed as [14]:

$$P_m = \frac{1}{2} \rho_{air} c_p \pi R^2 V_w^3 \quad (15)$$

Where ρ_{air} is the air density (1.225Kg/m³), R is the rotor radius (m) and V_w is the wind speed (m/s) and c_p is the power efficiency coefficient. The wind turbine just extracts a fraction of the power in the wind, and this fraction depends on the power efficiency coefficient. The Betz's limit defines the maximum limit for the power efficiency coefficient (c_p) as

0.59% of the kinetic energy on the moving wind. The power efficiency coefficient is a function of the turbine tip-speed ratio (λ) and turbine blade angle in degrees (β). The general expression to describe the power efficiency coefficient is:

$$c_p = c_1 \left(\frac{c_2}{\lambda_i} - c_3 \beta - c_4 \right) e^{\left(\frac{-c_5}{\lambda_i} \right)} + c_6 \lambda \quad (16)$$

Where the value of λ_i and λ are calculated as:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta + 1} \quad (17)$$

$$\lambda = \frac{\omega_{Turb}}{V_w} \quad (18)$$

where ω_{Turb} is the turbine rotational speed, the value of constant c_1 - c_6 is varying due to manufacturer data, The optimal operational point of a wind turbine at a given speed for extracting maximum power from the prevailing wind can be found from the wind turbine characteristics in Fig. 5.

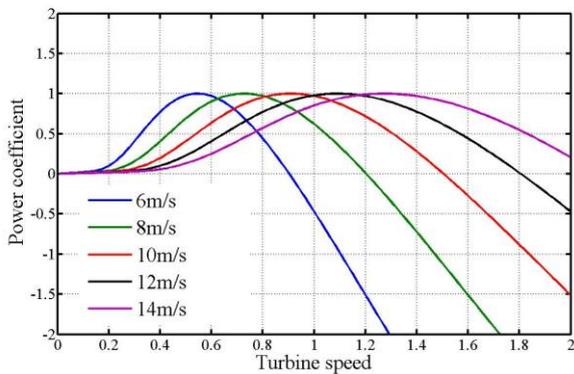


Fig. 5. Wind turbine characteristics

VI. SIMULATION RESULTS

The steady-state and transient performance of the test system shown in Fig. 3 is investigated to analysis the role of STATCOM in enhancing the wind farm and facilitate the compliance of required grid code. in this section. The ability of wind farm and STATCOM to provide voltage control at point of common coupling is studied during the variation of wind farm output power. At all case the voltage at PCC is maintained at 1.pu. While the capability of wind farm fault ride through capability is investigated during symmetrical fault at transmission line end terminal. As expected the wind farm remain connected to the system until the fault is cleared

I. Voltage Control during Wind Power variation

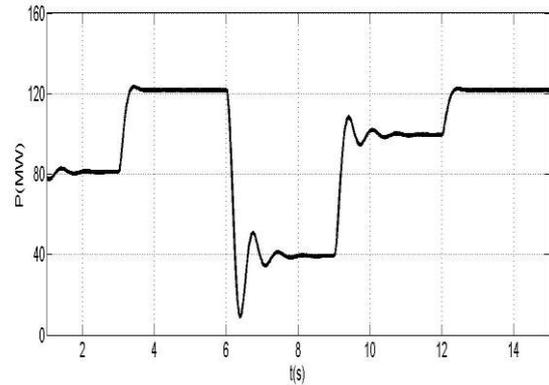
This section examines the ability of the proposed STATCOM to provide voltage support at PCC when the output power of wind farm varied due to variation in driven wind speed as shown below.

$$v=10m/s \ (0 \leq t \leq 3), \ v=14m/s \ (3 \leq t \leq 6), \ v=8m/s \ (6 \leq t \leq 9) \\ v=11m/s \ (9 \leq t \leq 12), \ v=11m/s \ (12 \leq t \leq 15)$$

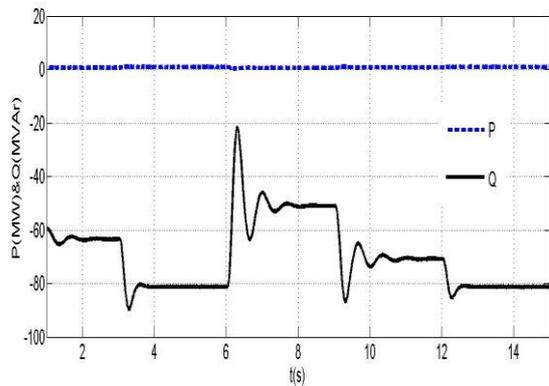
As shown in Fig.6a the output of the wind farm is varied as result of wind speed variation. The required reactive power by induction generator depend on the output of the machine, also the reactive power required to maintain the voltage at PCC depend on wind power injected into B1. It can be noticed that the proposed STATCOM has manipulated its reactive power exchange with the ac bus to maintain the voltage magnitude at

B₁ at 1.0 per unit as Fig.6b. As expected the voltage profile at B₁ is regulated at 1.0pu as shown in Fig.6c.

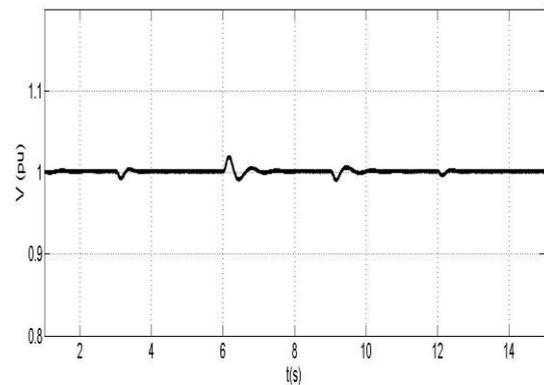
Fig. 6d shows current waveforms injected by the STATCOM into ac bus B₁ which is adjusted at wind speed variation.



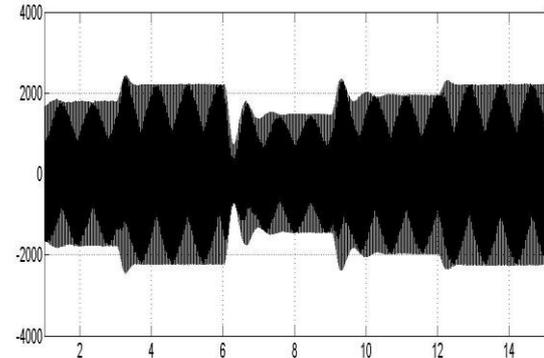
a. Wind farm active power generation



b. Active and reactive power of STATCOM exchange with ac network at bus B₁



c. AC voltage at point of common coupling (B1)



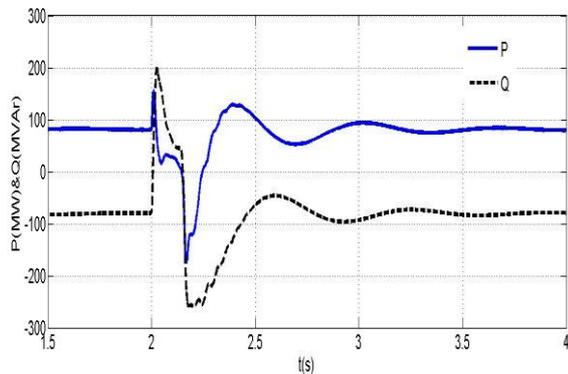
d- STATCOM Injected Current into B1

Fig. 6: Voltage waveforms illustrating the STATCOM capability to provide voltage support

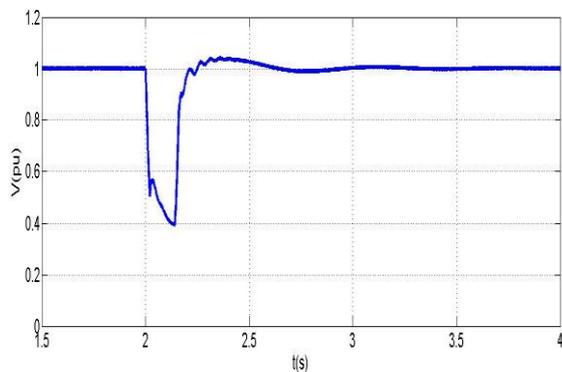
II. System Behavior during Symmetrical Fault

Fig. 7 shows the results obtained when the system in Fig. 2 is subjected to a three-phase fault at the end of the transmission line connected between buses B₁ and B₂, with fault duration of 140ms. It can be observed that wind farm remain connected to the system during the fault as state by grid code. Fig.7a shows the output of the wind farm which is subjected to transient oscillations during the fault period but recover to previous value successfully. The voltage at B₁ is decrease below the rated value but recover quickly to 1.0pu as shown in Fig.7b. The reactive power of STATCOM exchanges with the ac network has been adjusted in order to support the ac voltage at bus B₁ as shown in Fig.7c. Fig. 7d shows the waveforms of the currents that the STATCOM injects into ac bus B₁, which as can be seen, have been restrained during the fault period..

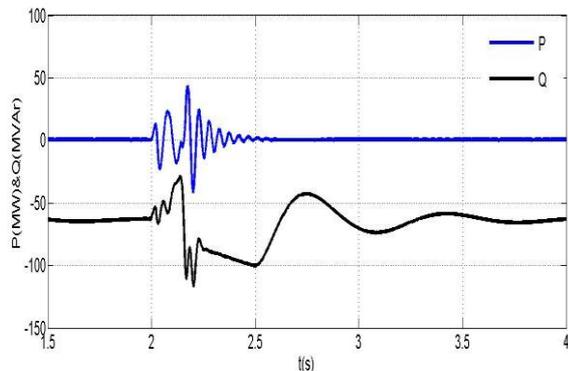
It can be observed that the STATCOM help in improving the fault ride through capability of the wind farm as specified in CC.6.3.15.1 in GB grid [15].



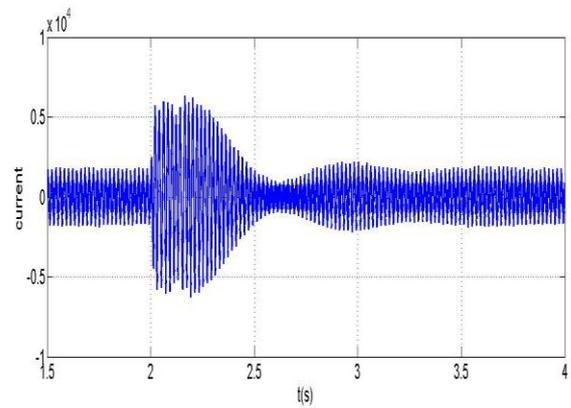
a. Wind farm active power generation



b. AC voltage at point of common coupling (B1)



c. Active and reactive power STATCOM



d. Current waveforms STATCOM injected into B1
Fig. 7: Voltage waveforms illustrating the STATCOM capability to provide voltage support

VII. CONCLUSION

This paper investigated the possible proper approaches for integration of FSIG wind farms to the power network. Improving the FSIG controllability to regulates the voltage at the PCC in necessary to fitful grid code requirement. The ability of STATCOM to control the reactive power and enhance the fault ride through capability utilised to eliminate the drawback of FSIG. FSIG with STATCOM and power storage devices is the new trend for reducing the operation problems associated fixed speed wind turbineas.

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