

Performance Enhancement of Wind Energy System with Distribution Static Compensator

Manju Aggarwal^{1*}, Madhusudan Singh² and S. K. Gupta¹

¹Department of Electrical Engineering, DCRUST, Murthal - 131039, Haryana, India;
manju14111@gmail.com, drskgupta.ee@dcrustm.org

²Department of Electrical Engineering, Delhi Technological University, Delhi - 110042, India;
madhusudan@dce.ac.in,

Abstract

Objectives: In this paper, dynamic performance of Wind Energy System (WES) comprising of Squirrel Cage Induction Generator (SCIG) is analyzed for grid connected operation with DSTATCOM. **Methods/Statistical analysis:** In the present work, modeling, analysis and working of a low voltage distribution system supported with wind energy conversion system is analyzed. A Distribution Static Compensator (DSTATCOM) has been modeled and simulated using MATLAB. The effectiveness of the proposed system has been verified by simulation and analytical results. The indirect current control technique is employed for present analysis as it is simple, robust and favourable as compared to other methods. **Findings:** The DSTATCOM improves the performance of Wind Energy System (WES) under transient condition i.e. change in wind speed and sudden change in load. The DSTATCOM augmented with wind energy system addresses the power quality and grid stability issues. **Application/Improvements:** The DSTATCOM in present study provides transient voltage support and also maintains the stability of a WES. When wind penetration increases beyond 30%, the system loses stability. A detailed simulations study is carried out on the application of DSTATCOM to improve the stability of the system

Keywords: DSTATCOM, Squirrel Cage Induction Generator (SCIG), Wind Energy System (WES), Wind Generator, Grid Code

1. Introduction

Global climate changes, increasing oil prices and depleting fossil fuel reserves are some of the reasons behind the increasing emphasis on the use of renewable energy¹. Renewable energy sources such as hydro, wind, solar, biomass and geothermal are alternatives to the conventional nuclear and fossil fuel power sources. Wind energy is a potential alternative to conventional sources as it is abundantly available. In the recent years many high rated wind turbines are being installed around the world. Wind energy technology^{2,3} has grown significantly during last few decades with the development of WTS of the early 1980s which generated a few kilowatts power rating to today's megawatt capacity single wind turbine. An increasing trend towards removal of dispersed single wind turbines by concentrated wind turbines in large wind energy sys-

tem has been extensively discussed by many researcher⁴⁻⁷. With the phenomenal growth and development in the last couple of decades, the WT industry has been moving forward with continuous improvement in WT efficiency and controllability⁸⁻¹⁰. Even after such rapid growth, its effective utilization through grid integration is yet to be fully exploited due to various challenges at both transmission and distribution levels. Typical challenges at transmission level are maintaining power angle, voltage and transient instability etc and that at the distribution level are how to effectively address the voltage instability, voltage dip, voltage unbalance, injection of harmonic currents and reactive power imbalance issues¹¹⁻¹⁵. Several researchers have worked in this area to understand the challenges and possible solutions to these problems. At transmission level, the grid instability is the main issue when wind energy penetration increases to 25-30% of short circuit

*Author for correspondence

power level of the grid. The use of STATCOM to improve stability and to reduce voltage variation due to fluctuation in wind speed is explained¹⁵. With the increasing trend of wind energy usage and penetration of wind turbine, the need to identify a standard operating practice for the wind turbines is being established in grid codes. This led to drafting of the grid code specifically for wind turbines in 2002¹⁶⁻¹⁸. The power quality issues are more prevailed on distribution level rather than on transmission level due to low short circuit capacity or X/R ratio of weak distribution feeder. The DSTATCOM is shunt connected device with similar structure as that of a STATCOM. A DSTATCOM is capable of injecting unbalanced and harmonically distorted current to eliminate unbalance and distortion supply current as against STATCOM which injects only set of balanced three phase voltages. The DSTATCOM is used to address power quality issues in low voltage grid with distributed energy sources¹⁹⁻²⁵. In the past few decades several types of wind turbine driven generators are deployed in WES i.e. constant speed with Squirrel Cage Induction Generator (IG), Variable Speed generators like Doubly-Fed Induction Generators (DFIGs), Direct Drive Permanent Magnet Synchronous Generator (PMSG), coupled with gearbox and full rating power converters²⁴⁻²⁶. However, Induction Generator (IG) based wind energy conversion system still represent 15% of the installed wind power in Europe²⁷ which is significantly high and hence there is a need to enhance the performance of such type of generators. The induction generator based wind energy conversion system²⁸⁻³¹ consumes large amount of reactive power during voltage dips and hence vulnerable to grid instability.

This paper investigates the performance of grid connected wind energy system along a DSTATCOM in to a low voltage distribution system with different short circuit ratio. The simulation results demonstrate the effect of integrating wind energy system on grid and also role of DSTATCOM for the required compensation. The DSTATCOM in present study maintains stability and compensates for the load and generator reactive power, load unbalancing and harmonics elimination from source current. This enables the grid operator to supply quality electricity to the end users.

1.1 System Description

The simulated system consists of 11 kV, 50 Hz distribution system along with a wind energy system directly

connected to the grid and DSTATCOM on the point of common coupling as shown in Figure 1. The distribution system consists of a transformer with a voltage of 415 V at the Point of Common Coupling (PCC). The WES system has three Squirrel Cage Induction Generators (SCIG) driven by a fixed speed wind turbine. The DSTATCOM consists of three leg IGBT based Voltage Source Converter (PWM-VSC) with a DC bus capacitor. It supplies the lagging or leading current to manage the constant terminal voltage, harmonic currents and unbalanced currents. A hysteresis PWM current controller is used to manage the gating pulses for the IGBT switches. The Short Circuit Ratio (SCR) of the distribution system is the ratio of short circuit power level of the grid (S_{sc}) to rated turbine power level (S_r)

$$R_{sc} = \frac{S_{sc}}{S_r} \quad (1)$$

A ratio below 10 usually means a weak grid³². As SCR decreases below 10, voltage drop increases until system stability is lost.

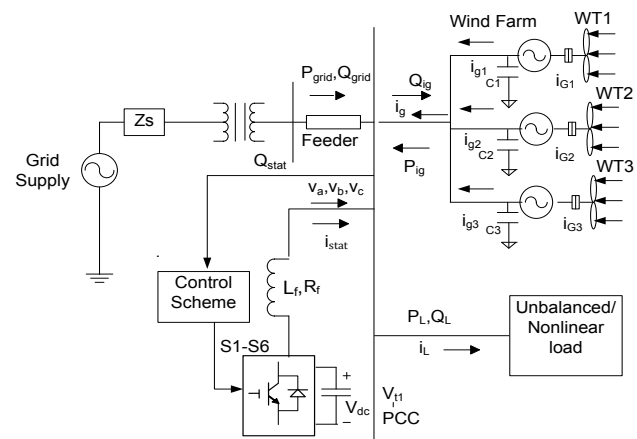


Figure 1. Basic structure of test system.

2. Model Equations of SCIG in Wind Generation System

The electrical system consists of asynchronous generator using conventional squirrel cage induction machine. The equivalent SCIG model is established using rotating field (d, q) reference³³. The stator and rotor voltage equations of a SCIG are given by following equations

$$v_{ds} = R_s i_{ds} + \frac{d}{dt} \lambda_{ds} - \omega_e \lambda_{qs} \quad (2)$$

$$v_{qs} = R_s i_{qs} + \frac{d}{dt} \lambda_{qs} + \omega_e \lambda_{ds} \quad (3)$$

$$v_{dr} = R_r i_{dr} + \frac{d}{dt} \lambda_{dr} - (\omega_e - \omega_d) \lambda_{qr} \quad (4)$$

$$v_{qr} = R_r i_{qr} + \frac{d}{dt} \lambda_{qr} + (\omega_e - \omega_d) \lambda_{dr} \quad (5)$$

Where $v_{ds}, v_{qs}, v_{dr}, v_{qr}$ are the direct and quadrature axes stator and rotor voltage. R_s, R_r are per phase stator and rotor resistances. $i_{ds}, i_{qs}, i_{dr}, i_{qr}$ are the direct and quadrature axes stator and rotor currents and ω_e and ω_d synchronous speed and electrical rotor speed respectively

Where $v_{dr} = v_{qr} = 0$ for squirrel cage rotor. The stator and rotor flux can be computed as function of the d-and q-axes stator and rotor currents as follows:

$$\lambda_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) \quad (6)$$

$$\lambda_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i_{qr}) \quad (7)$$

$$\lambda_{dr} = L_{lr} i_{dr} + L_m (i_{dr} + i_{ds}) \quad (8)$$

$$\lambda_{qr} = L_{lr} i_{qr} + L_m (i_{qr} + i_{qs}) \quad (9)$$

Where $\lambda_{ds}, \lambda_{qs}, \lambda_{dr}, \lambda_{qr}$ are the flux linkages of the stator and rotor respectively. Electromagnetic torque is expressed as:

$$T_e = \left(\frac{3}{2}\right) \left(\frac{P}{2}\right) L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \quad (10)$$

Where L_m is the mutual inductance and P is the total number of poles in each SCIG.

3. DSTATCOM Control Algorithm

The current compensating feature of a DSTATCOM is described by the following equations. The instantaneous value of various currents in a WES and DSTATCOM before transformation are written using Kirchhoff's current law as

$$i_{grid}(t) = i_L(t) - i_{stat}(t) - i_g(t) \quad (11)$$

$$i_g(t) = i_{g1}(t) + i_{g2}(t) + i_{g3}(t) \quad (12)$$

Where i_{grid}, i_L, i_{stat} and i_g are the grid current, load current, compensator current and wind energy system current respectively.

i_{g1}, i_{g2} and i_{g3} are the currents supplied by each wind generator.

The developed instantaneous source voltage is

$$v_{grid}(t) = v_m \sin \omega t \quad v_{grid}(t) = v_m \sin \omega t \quad (13)$$

Where $\omega t = \theta$ and v_m is the peak amplitude of supply voltage

Compensating currents provided by DSTATCOM to make utility voltage purely sinusoidal are given by equation (14)

$$i_{stat}(t) = i_L(t) - i_{grid}(t) - i_g(t) \quad (14)$$

The source currents need to be sinusoidal for ideal compensation, irrespective of the nature of the load. The grid synchronization is obtained through a Phase Locked Loop (PLL) for generating angle θ and to derive unit vector template for reference source vector for the current of DSTATCOM.

$$u_a = \sin(\theta) \quad (15)$$

$$u_b = \sin\left(\theta - \frac{2\pi}{3}\right) \quad (16)$$

$$u_c = \sin\left(\theta + \frac{2\pi}{3}\right) \quad (17)$$

The in phase component of reference currents i_{dabc}^* are derived using in phase unit vector template as

$$i_{da}^* = I_d^* \cdot u_a \quad (18)$$

$$i_{db}^* = I_d^* \cdot u_b \quad (19)$$

$$i_{dc}^* = I_d^* \cdot u_c \quad (20)$$

Where I_d^* is the output of PI controller regulating dc bus voltage of DSTATCOM. Figure 2 shows the block diagram of control scheme for DSTATCOM.

Quadrature components of reference current are obtained as follows

$$w_a = -\frac{u_a}{\sqrt{3}} + \frac{u_c}{\sqrt{3}} \quad (21)$$

$$w_b = \sqrt{3} \frac{u_a}{2} + \frac{u_b - u_c}{2\sqrt{3}} \quad (22)$$

$$w_c = -\sqrt{3} \frac{u_a}{2} + \frac{u_b - u_c}{2\sqrt{3}} \quad (23)$$

Quadrature component of reference source current (i_{qabc}^*) (i_{qabc}) is calculated by multiplying w_a, w_b, w_c with the quadrature component of current (i_{1q}) which is obtained by controlling AC voltage. Regulation of AC terminal voltage is achieved by comparing it with the reference voltage i.e. maximum value of desired voltage (V_{tref}) at PCC. A PI controller processes the voltage error. The amplitude of reactive current (I_q^*) to be produced by the DSTATCOM is decided by the output of the PI controller in AC voltage control loop. This enables the source current controlling to be sinusoidal.

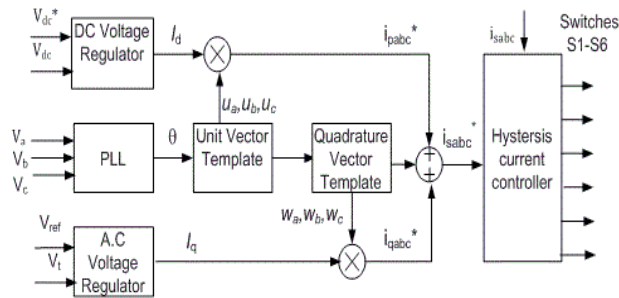


Figure 2. Control scheme of DSTATCOM.

4. Simulation Results and Discussion

Impact of a wind energy system on distribution system with and without static compensator is analysed for various types of load with different short circuit ratio on grid. The waveforms of the grid active and reactive powers (P_{grid} , Q_{grid}), load powers (P_L , Q_L), wind generator powers (P_{ig} , Q_{ig}), voltage at point of common coupling (V_{pcc}) and grid current (i_{grid}), load current (i_L), controller current (i_{stat}), DC link voltage (V_{dc}) and r.m.s voltage at the point of common coupling (V_{t1}) etc. are shown with and without controller. Positive values of active/ reactive power of wind generator, grid and DSTATCOM imply that these powers flow from grid side towards PCC where as the active and reactive powers consumed by the load are represented by positive sign.

4.1 Behaviour of Low Voltage Distribution System under Unbalanced/Nonlinear Load

The behaviour of the 11 kV, 0.75 MVA, 50Hz feeder system with unbalanced/nonlinear load has been shown in Figure 3. The simulation model consists of a simple 11 kV feeder supplying diverse nature of linear/nonlinear load. Nonlinear load consists of three phase diode rectifier with resistive load of 8kW and L-C filter at dc side. At $t = 0.7$ sec nonlinear as well as unbalanced load is switched on into the system and it has been observed that load power of 38 kW is supplied by the grid only. Rest of the active power (1 kW) and reactive power is supplied by the grid to compensate the feeder impedance. Figure 3 shows that when unbalanced load of 5kW in phase 'a', 7kW in phase 'b' and 12 kW in phase 'c' and nonlinear load are switched on into the system, there is a 14% drop in the voltage at PCC. Grid currents (i_{grid}) and load currents (i_L) are unbalanced and nonlinear.

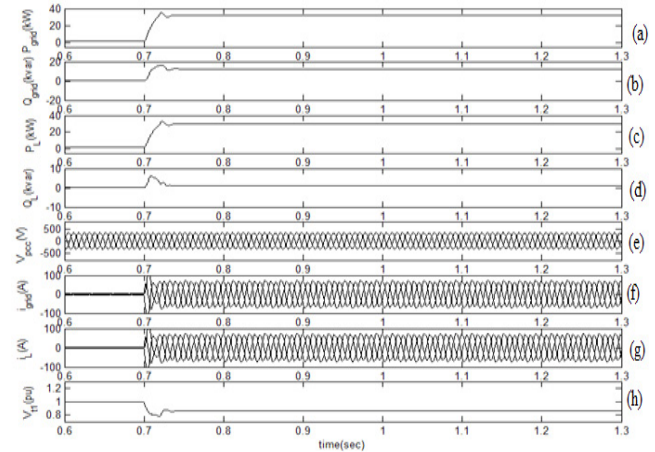


Figure 3. (a) Pgrid (b) Qgrid (c) load (PL) (d) QL (e) Vpcc (f) igrid (g) iL (h) Vt1 without wind generator and DSTATCOM.

4.2 Behaviour of Low Voltage Distribution System under Unbalanced/Nonlinear Load with 10% Wind Penetration

Figure 4 shows behaviour of the distribution system when a wind energy system consisting of three wind generators is connected to the low voltage distribution system. At $t=0.6$ sec, most of the power generated by a wind energy system is supplied to the grid due to small load (2 kW) as evident from Figure 4. At $t=0.7$ sec., load increases from 2 kW to 38 kW, the power generated by a wind generator (15 kW) is fully consumed by the load and remaining (24 kW) is supplied by the grid. With the increase in wind speed from 8 m/s to 11 m/s at $t=1.2$ sec, the maximum power tracking is achieved by increasing the pitch angle from 0 to 9 using pitch controller. At this point, power generated by the wind generator is increased to 22kW and grid supplies the remaining power of 16 kW. But reactive power burden on grid increases by connecting a wind generator into the system as induction generator draws the reactive power proportional to active power supplied by it. The grid current (i_{grid}) becomes unbalanced and nonlinear because of the nature of the load as shown in Figure 5. Wind generator current i_g is also unbalanced and nonlinear. A dip in pcc voltage (V_{t1}) is also observed.

4.3 Performance of Low Voltage Distribution System for 30% Wind Penetration without DSTATCOM

Figure 6 shows behavior of the system when a wind energy system consisting of 30% of grid capacity is connected to

low voltage distribution system. The short circuit ratio of (3) leads to voltage instability at PCC due to reasonable reactive power requirement of wind generator. The Voltage at the V_{PCC} decreases to 0.2pu. Figure 6 shows that speed of induction generator (w) monotonically increases which indicates clear instability.

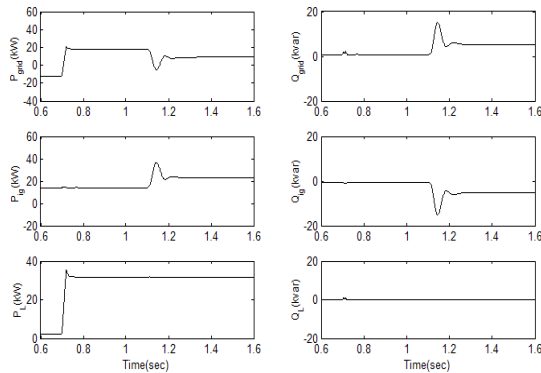


Figure 4. Profile of active and reactive powers of grid (P_{grid} , Q_{grid}), wind energy system (P_{ig} , Q_{ig}) and load (P_L , Q_L) without DSTATCOM.

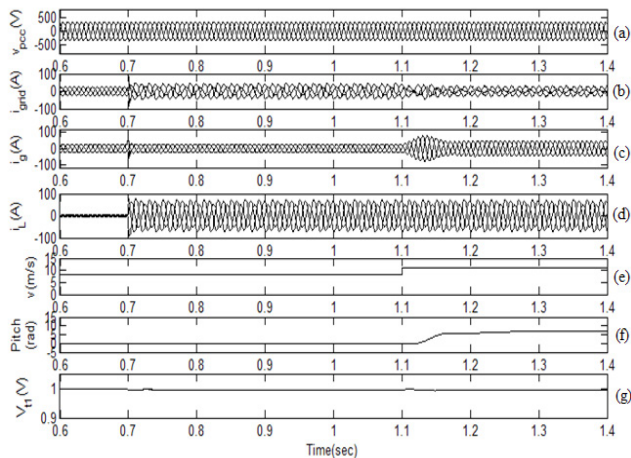


Figure 5. (a) V_{pcc} (b) i_{grid} (c) i_g (d) i_L (e) wind speed (f) Pitch angle (g) V_{t1} with 10% wind generation without DSTATCOM.

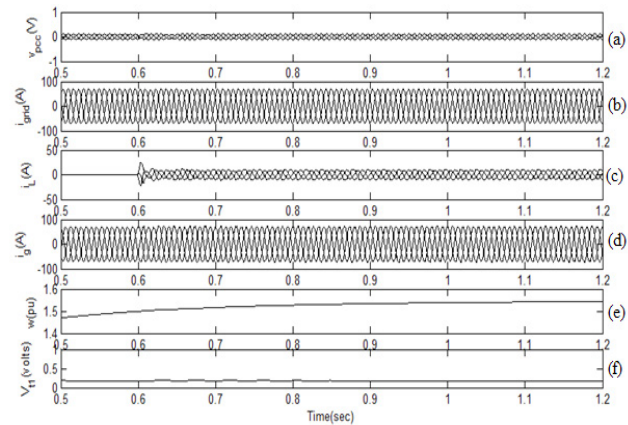


Figure 6. (a) V_{pcc} (b) i_{grid} (c) i_L (d) i_g (e) Generator speed (g) V_{t1} with 30% wind generation without DSTATCOM.

4.3 Performance of Low Voltage Distribution System with 10% Wind Penetration with DSTATCOM

Performance of the system is analysed with DSTATCOM for 10% and 30% wind penetration as shown in Figure 8 and Figure 9. The power exchange among different system components are shown in Figure 7. In the absence of a DSTATCOM, a dip in voltage is observed and grid currents and generator currents were also unbalanced and nonlinear. The active-reactive powers of grid (P_{grid} , Q_{grid}), load (P_L , Q_L) and DSTATCOM (P_{stat} , Q_{stat}) are also shown in Figure 7. The magnitude and nature of power flow during the operation of this system are also given in Table 1. It is observed that magnitude of terminal voltage (V_{t1}) stays constant and DC link voltage (V_{dc}) adjusts at the reference value. Since there active power requirement of wind generator is now supplied by DSTATCOM completely, there active power burden on the grid is reduced. DSTATCOM helps in balancing the load unbalance and supplying the reactive power required by wind generator, hence improving the grid power quality. Figure 8 and Figure 9 shows the voltage at the point of common coupling (V_{pcc}) grid current (i_{grid}), generator current (i_g),

Table 1. Balance of active and reactive power between generation and load

415V, 50Hz Distribution system connected with load							
P_{grid}	Q_{grid}	P_{ig}	Q_{ig}	P_{stat}	Q_{stat}	P_L	Q_L
39kW	9kvar	0	0	0	0	38 kW	1kvar
415V, 50 Hz Distribution system connected with wind generator and load							
24kW	4.6kvar	15kW	-3.6kvar	0	0	38kW	1kvar
415V, 50 Hz Distribution system connected with wind generator, load and DSTATCOM							
17kW	-1.5kvar	22kW	-10kvar	0	16kvr	38kW	1kvar

load current (i_L), which are also balanced by connecting DSTATCOM into the system. The generator speed is also constant at 1.04 pu. Total Harmonic Distortion (THD) of grid current with static compensator is 0.85% which meets the grid code requirements. Table 2 shows the balance of active and reactive power before and after switching on load.

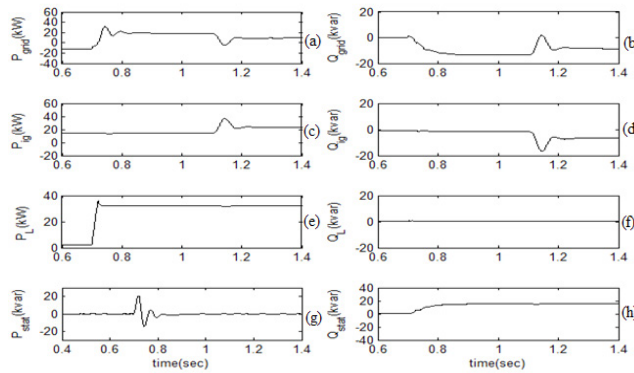


Figure 7. (a) Pgrid (b) Qgrid (c) Pig (d) Qig (e) PL (f) QL (g) Pstat (h) Qstat.

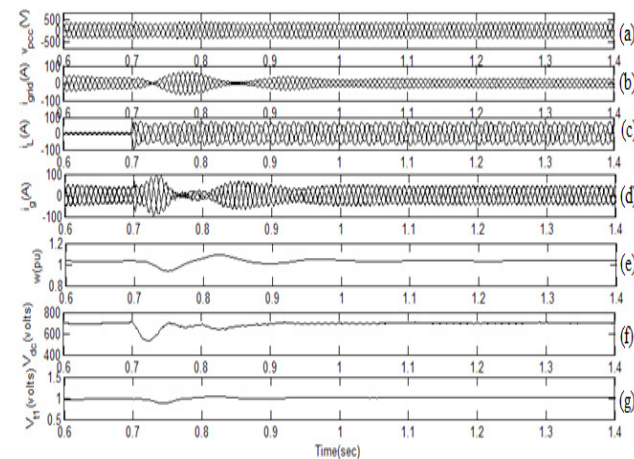


Figure 8. (a) Vpcc (b) igrid (c) ig (d) iL (e) Wind speed (f) Vdc (g) Vt1 with 30% wind generation with DSTATCOM.

Table 2. Balance of active and reactive power between generation and load

Source/sink	0-0.7sec	0.7-1.0sec	1.2-1.6sec
P_{grid}	-15.0kW	23kW	16kW
Q_{grid}	7kvar	-4.6kvar	-1kvar
P_{ig}	15 kW	15 kW	22kW
Q_{ig}	-1 kvar	- 3kvar	-10kvar
P_L	2 kW	38 kW	38kW
Q_L	1kvar	0.3kvar	0.3kvar
Q_{stat}	1.3 kvar	17 kvar	19kvar

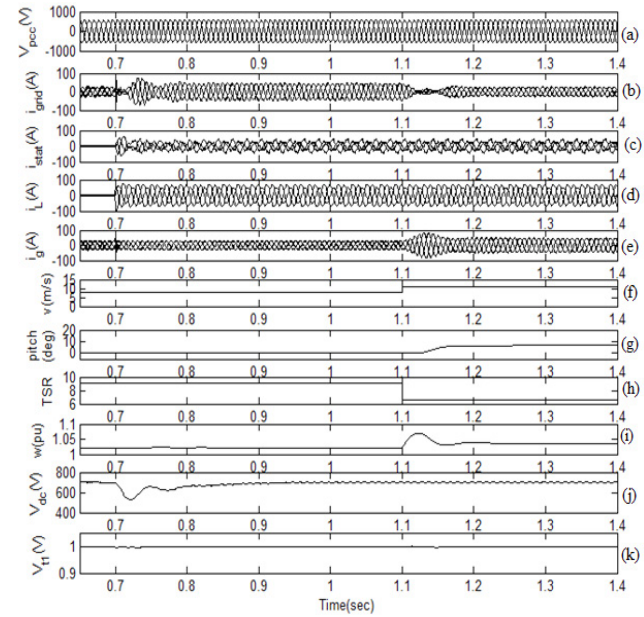


Figure 9. (a) Vpcc (b) igrid (c) istat (d) i_L (e) ig (f) Wind speed (g) Pitch angle (h) TSR (i) Gen. speed (j) Vdc (k) Vt1 with 10% wind generation and DSTATCOM.

5. Conclusion

Effect of integrating a Wind Energy System in the low distribution system with different short circuit ratio and operation with DSTATCOM has been demonstrated in this paper. The system loses stability when wind penetration increases beyond 30%. The complete power flow analysis with and without distribution static compensator is also presented. The DSTATCOM has capability to enhance the performance of a wind energy system with good voltage regulation, harmonic elimination and load balancing.

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