Modeling of a Grid compatible Variable Speed Wind Turbine with direct drive Synchronous Generator

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***Abstract*— This paper presents the modeling and simulation of a grid compatible variable speed wind turbine (VSWT) with direct drive synchronous generator (DDSG) and power electronics interface. Models and equations of wind turbine, DDSG with field excitation controller and power electronics controller interface are presented and their implementations are explained. Controllable voltage source converter(VSC) with hysteresis band current control are utilized for capturing the maximum power under variable speed operation and maintaining reactive power generation at a desirable level. The control strategy of this model can be employed to regulate the real power, reactive power, generated voltage and generated speed at different wind speeds in the power system. Simulation results are presented which provides the control performance and dynamic behavior of a VSWT with DDSG.**

Keywords- VSWT, DDSG, VSC with hysteresis band current control, maximum power capture, reactive power control.

I. INTRODUCTION

Wind energy is a reliable, natural and renewable electrical power supply. The high installed capacity of today's wind turbines and decreasing plant costs have shown that wind power can be competitive with conventional, more heavily polluting, fuels in the long term. In terms of wind power generation technology, as a result of numerous technical benefits (higher energy yield, reducing power fluctuations and improving VAR supply) the modern MW-size wind turbines always use variable speed operation which is achieved by power electronic converters. Interconnecting large wind farms to power grids and the relevant influences on the host grids need to be carefully investigated. To increase the maximum power extraction the variable speed generators are employed. These variable speed generators necessitate AC-DC-AC conversion systems [1]. The modeled system includes a fixed-pitch, stall regulated wind turbine, a DDSG and a controllable power electronics system, which consists of an uncontrolled rectifier and VSC with hysteresis band current control. The purpose of modeling is to support the project in its architecting effort. The project purpose is always to realize a system in its context. A good system is a system that fits in its context and that is appropriate for its purpose. The schematic diagram of the modeled VSWT driven synchronous generator is shown in Figure 1.

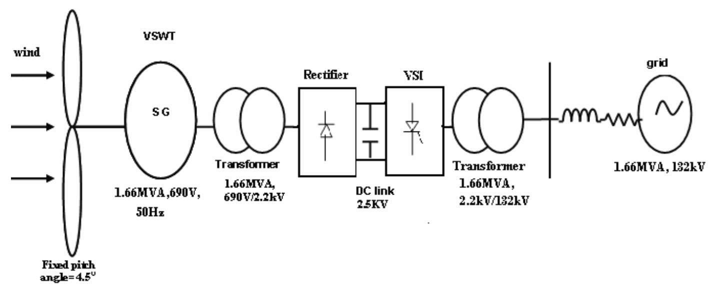

Figure 1. Schematic diagram of modeled VSWT with DDSG

II. SUBSYSTEM MODELS

The VSWT model consists of the following components.

- Wind turbine and control
- DDSG
- Rectifier and inverter

A. Wind Turbine

The wind turbine is described by the following equation (1) (2) and (3) where λ is the tip speed ratio, ω_M is the mechanical speed of wind turbine in rad/sec., R is the blade radius in m, V_W is the wind speed in m/sec., P_M *is* the mechanical power from wind turbine in kW, ρ is the air density in kg/m^3, C_P is the power coefficient and T_M is the mechanical torque from wind turbine in N-m.

$$\lambda = \frac{\omega_M R}{V_W} \quad (1)$$

$$P_M = \frac{1}{2}\rho\pi R^2 C_P V_W \quad (2)$$

$$T_M = \frac{P_M}{\omega_M} = \frac{1}{2}\rho\pi R^5 C_P \frac{\omega_M^2}{\lambda^3} \quad (3)$$

The mechanical torque obtained from equation (3) enters as the input torque to function of the tip speed ratio (TSR) λ given by equation (2).

$$C_P = (0.44 - 0.0167\beta)\sin\frac{\pi(\lambda - 2)}{13 - 0.3\beta} - 0.00184(\lambda - 2)\beta \quad (4)$$

where β is the blade pitch angle. For a fixed pitch type, the value of β is set to a constant value of 4.5^0. For a gearless WT, the drive train is simulated by a single, lumped inertia.

B. DDSG with field excitation (Ef) controller

The synchronous generator is simulated by the standard 5th order dq dynamic model, [2].The generator is rated 1.66MVA, 690V/50Hz and its number of poles is equal to 70, resulting in a nominal speed equal to the maximum rotor speed. The generator terminal voltage is rectified to feed the field winding. The excitation voltage is regulated via the Ef controller [3] of Figure 2, which has sufficient over-excitation capability.

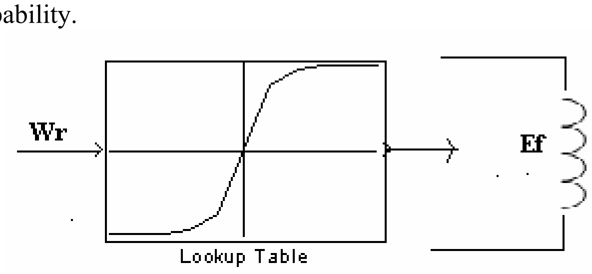

Figure 2. Ef controller

By excitation control, constant voltage can be maintained and it helps the dc link to meet the adequate level of inverter output voltage as given in (6) below

$$Vdc \geq \frac{2\sqrt{2}\ V_{AC-RMS}}{D_{MAX}} \quad (5)$$

where V_{AC-RMS} is RMS line to neutral voltage of the inverter and D_{MAX} is maximum duty cycle. Since the synchronous generator is a direct drive type with low speed and a high number of poles, the wind turbine and the generator are rotating at the same mechanical speed via the same shaft. Therefore, shaft dynamics can be characterized by a swing equation on a single mass rotating shown in equation (6).

The shaft dynamics and the rotating mass can be easily interfaced with the synchronous machine model.

$$J_M \frac{d\,\omega_M}{dt} = T_M - T_E - D\omega_M \quad (6)$$

where J_M is the a single rotating inertia in kg-m^2,T_E is the electric torque produced by generator in N-m and D is the damping J-s/rad.

In variable speed operation, the rotating speed of the wind generator is not consistent with the electrical synchronous speed of the electric network and generally much slower than the speed. The electrical base frequency of the machine in the built-in models must be set to a value corresponding to the rated mechanical speed of the wind turbine specified by a manufacturer or a designer. Equation (7) and (8) give the value for the electrical base speed of the synchronous machine ω_B.

$$f_B = \frac{N_P}{2}\frac{RPM_{TUR}}{60} \quad (7)$$

$$\omega_B = 2\pi f_B = \pi \cdot N_P \cdot \frac{RPM_{TUR}}{60} \quad (8)$$

where f_B is the electrical base frequency of the generator in Hz., P is the number of poles and RPM_{TUR} is the mechanical rated speed of the turbine in rpm.

One important advantage of the synchronous generator is its ability to supply either inductive or capacitive reactive power to a load. Most loads require some reactive power for operation, so the synchronous generator can meet all the requirements of a load while requiring nothing from the load. It can operate in an independent mode as well as intertied with a utility grid.

C. Power electronics control

In this work, system is interfaced with an uncontrolled rectifier and three phase VSC with hysteresis band current control which is less expensive than others and commonly put into industrial use, has been modeled [4] for AC-DC–AC conversion. Figure 3 shows a rectifier and inverter circuit for VSWT modeling. The uncontrolled rectifier converts ac power generated by the wind generator into dc power and it is given to VSC in turn is supplied to voltage grid system.

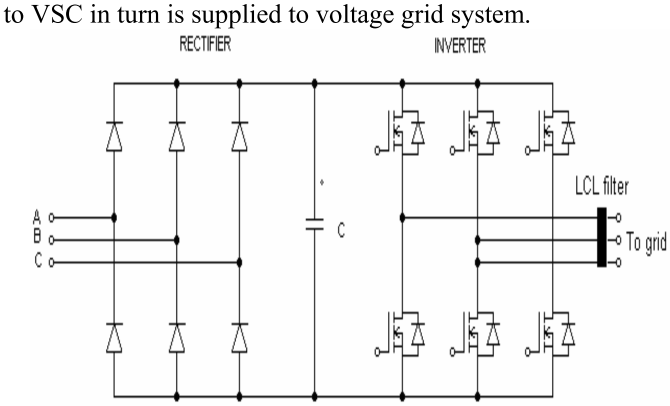

Figure 3. Rectifier and VSC circuit for VSWT modeling

The VSC is a voltage harmonic source in the point of view of AC system and a harmonic filter need be placed appropriately to reduce the voltage harmonics it generates [5] . When connecting a VSC to a grid, an inductor must be mounted between the VSI which is operating as a stiff voltage source, and the grid, which also operates as a stiff voltage source. Here an LCL filter is used which reduces the resonance problem and lowers the grid current distortion. A LCL harmonic filter consisting of a series interconnection of inductors and a parallel capacitor is located at the VSI terminal. Current-controlled VSCs can generate an AC current which follows a desired reference waveform so can transfer the captured real power along with controllable reactive power. For the modeling study, d-q control method that is widely used for VSC current control is employed. Figure 4 shows the VSC with hysteresis band current control scheme.

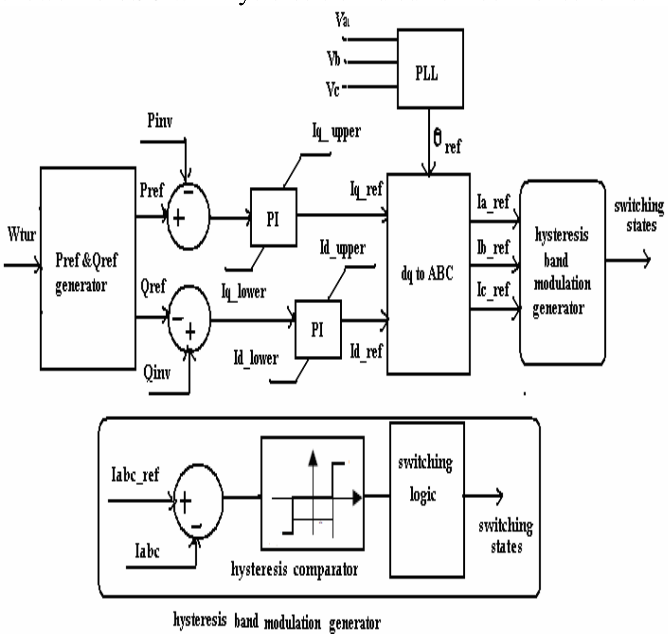

Figure 4. Hysteresis band current control scheme of VSC

P_{ref} and Q_{ref} are the desired real and reactive power. P_{inv} and Q_{inv} are the actual real and reactive power. P_{ref} and Qref can be calculated by using the following equations (9), (10) & (11).

$$P_M^{MAX} = \frac{1}{2}\pi\rho R^5 \frac{C_P^{MAX}}{\lambda_{OPT}^3}\omega_M^3 \tag{9}$$

$$P_{ref} = \eta P_M^{MAX} \tag{10}$$

$$Q_{ref} = P_{ref} \cdot \frac{\sqrt{1-PF^2}}{PF} \tag{11}$$

where η is the electrical efficiency of generator and inverter.

The reactive power generation is limited by reactive power capability of the VSWT. The limits of reactive power capability are calculated by equation (12).

$$Q_{limits} = \pm\sqrt{\left(S_{inv}^2 - P_{inv}^{\ 2}\right)} \tag{12}$$

The d–q transformation control [7] described by equation (13) is applied to enable real and reactive component of ac output power to be separately controlled. The variables in the *a–b–c* coordinate may be transformed into those in the d–q coordinate.

$$I_{dqo} = TI_{abc} = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos(\theta) & \cos(\theta-\frac{2\pi}{3}) & \cos(\theta+\frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta-\frac{2\pi}{3}) & \sin(\theta+\frac{2\pi}{3}) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{13}$$

θ = phase angle of V_a in radian .The dqo transformation is a mathematical transformation used to simplify the analysis of three-phase circuits. Here it is used to simplify calculations for the current control scheme of VSC. The instantaneous active and reactive power, P and Q are calculated by equation (14) & (15)

$$P = \frac{3}{2}|V_O|I_q \tag{14}$$

$$Q = -\frac{3}{2}|V_O|I_d \tag{15}$$

where $|V_O|$ is the instantaneous VSWT voltage magnitude. $|V_O|$ is almost as constant as grid ac voltage. So the real and reactive power can be controlled by regulating the q- and d-axis current, I_q and I_d respectively. The errors between P_{ref} and Q_{ref} and between Q_{ref} and Q_{inv} are processed into the $I_{q\ ref}$ and $I_{d\ ref}$, respectively through proportional-integral (PI) control gains. $I_{q\ ref}$ and $I_{d\ ref}$ are then transformed into $I_{a\ ref}$, $I_{b\ ref}$ and $I_{c\ ref}$ by the inverse transform given in equation (16).

$$I_{abc} = T(\theta)^{-1}I_{dqo} = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos(\theta) & \sin(\theta) & \frac{\sqrt{2}}{2} \\ \cos(\theta-\frac{2\pi}{3}) & \sin(\theta-\frac{2\pi}{3}) & \frac{\sqrt{2}}{2} \\ \cos(\theta+\frac{2\pi}{3}) & \sin(\theta+\frac{2\pi}{3}) & \frac{\sqrt{2}}{2} \end{bmatrix}\begin{bmatrix} I_d \\ I_q \\ I_o \end{bmatrix} \tag{16}$$

A phase-locked loop (PLL) is a control system that tries to generate an output signal whose phase is related to the phase of the input "reference" signal. Here, PLL generates a signal synchronized in phase to the inverter output voltage V_a to provide the reference phase angle θ_{ref} for the rotational inverse d–q transformation $T(\theta)^{-1}$.

The current reference values $I_{a\ ref}$, $I_{b\ ref}$ and $I_{c\ ref}$ are compared with the actual current of I_a, I_b and I_c of VSWT. The output current error is fed to a hysteresis comparator [6]. The switching frequency of hysteresis band modulator is large and constant. It increases the rise time and makes settling time less. So steady state can be fastly reached. It has a fast response to rapid variations in reference currents with a small delay. The characteristics of hysteresis band modulator are represented as in equation (17) [7].

$$a = \begin{cases} 0 \text{ if } \Delta i_o < -h/2 \\ 1 \text{ if } \Delta i_0 > +h/2 \end{cases} \tag{17}$$

where h is the width of the loop, a is a variable and i_o the current error. The hysteresis band modulation tracks the reference current within a hysteresis band. If the current exceeds the upper limit of the hysteresis band, the upper switch of the inverter arm is turned off and the lower switch is turned on. As a result, the current starts to decay. If the current crosses the lower limit of the hysteresis band, the lower switch of the inverter arm is turned off and the upper switch is turned on. As a result, the current gets back into the hysteresis band. Hence, the actual current is forced to track the reference current within the hysteresis band to turn ON or OFF the inverter switches. Thus voltage across the capacitor Co can be kept constant.

III. SIMULATION RESULTS AND ANALYSIS

Table 1 and Table 2 provides the parameters of wind turbine model and parameters of the EESG respectively. Figure 1 presents the modeling and simulation of a grid compatible VSWT with DDSG system implemented in MATLAB/Simulink. For the variable speed operation of the WECS, a step change in wind speed is used in MATLAB, with a step size of 0.5, a wind speed of 8 m/sec. and 7.5 m/sec. is considered in this system is shown in Figure 5.

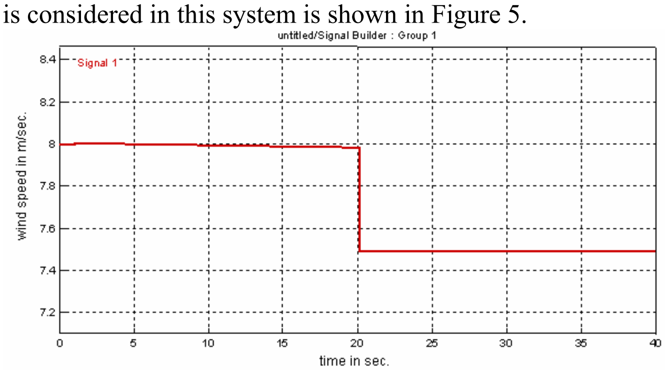

Figure 5. Wind speed

A glitch occurred in Figure 6 and Figures (8-13) is due to this change in wind speed.

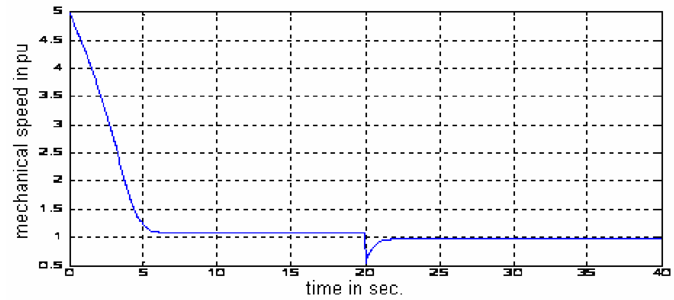

Figure 6. Mechanical speed (2.808 rad/sec) of VSWT with DDSG

Figure 6 presents the turbine angular speed variation in response to the varying wind speed. The rotor speed has varied smoothly in response to changes in wind speed, owing to the inertia of the turbine and generator.

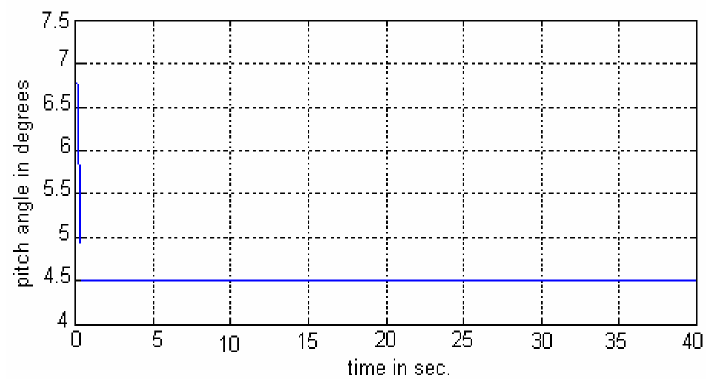

Figure 7. Constant pitch angle (4.5^0) of VSWT with DDSG

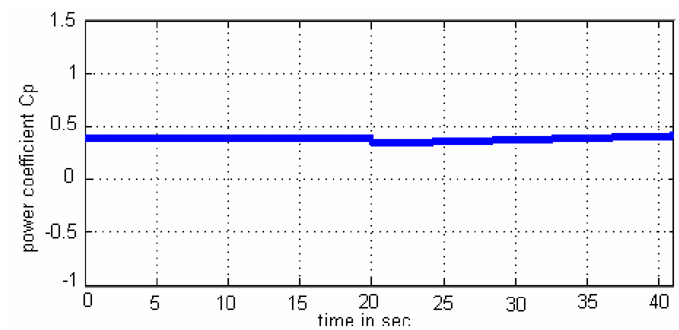

Figure 8. Power coefficient maintained at 0.4

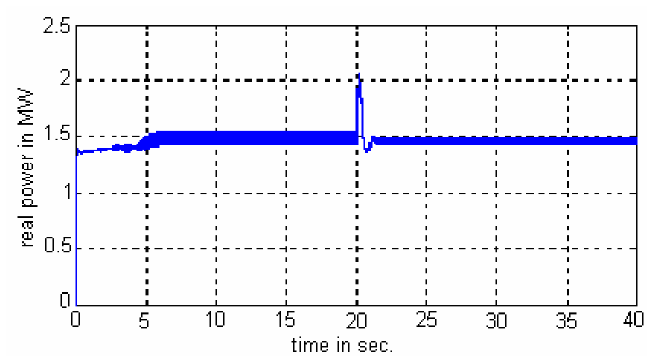

Figure 9. Real power output (1.5MW) of VSWT with DDSG

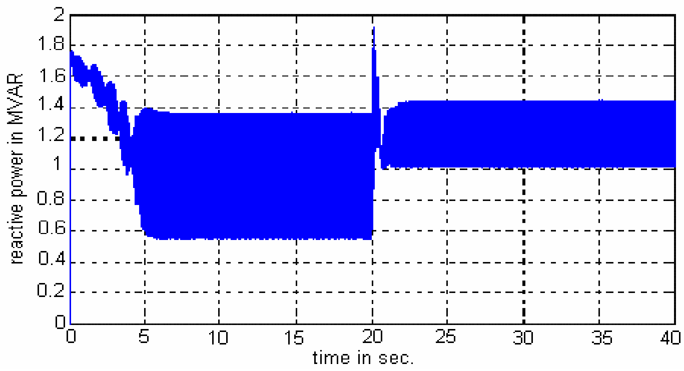

Figure 10. Reactive power generated by VSWT with DDSG

Figure 9 &10 present the real and reactive power of the VSWT. The real and reactive power have varied smoothly. This is possible due to the inertia smoothing effect and VSC interface control.

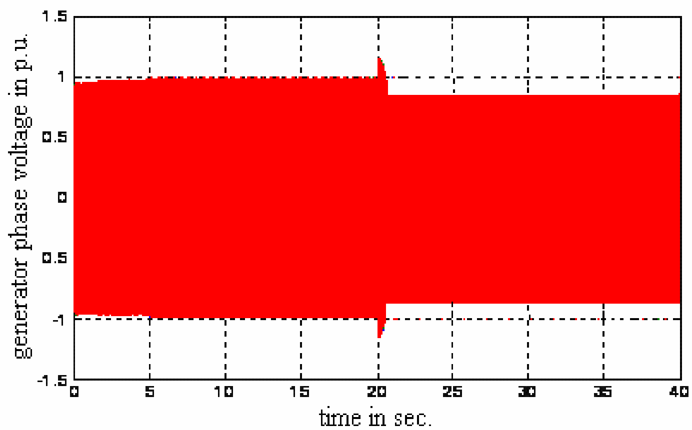

Figure 11. Generated phase voltage in p.u. (690V) of VSWT with DDSG

The VSWT voltage variation is given in Figure 11 and the voltage magnitude fluctuated with wind speed. This VSWT output voltage is stepped to 2.2kV by a step up transformer. The rating of the grid interface VSI is 1.8 MVA and the hysteresis band width is chosen to be 0.7.

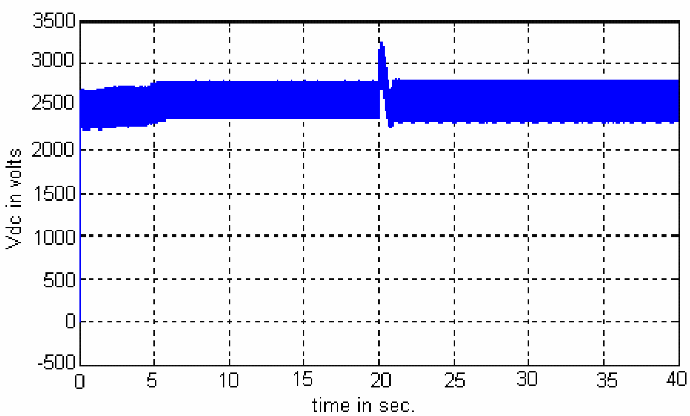

Figure 12. Vdc link (2.5kV)of VSWT with DDSG

Figure 12 shows the dc link voltage and it was maintained at a level 2.5 kV sufficient to meet the ac conversion requirement. The capacitor value of grid interface rectifier is 2500uF and d.c link voltage is 2.5 KV. The transformer rating of grid connected side is 2.2kV/132kV. The grid voltage is 132kV.

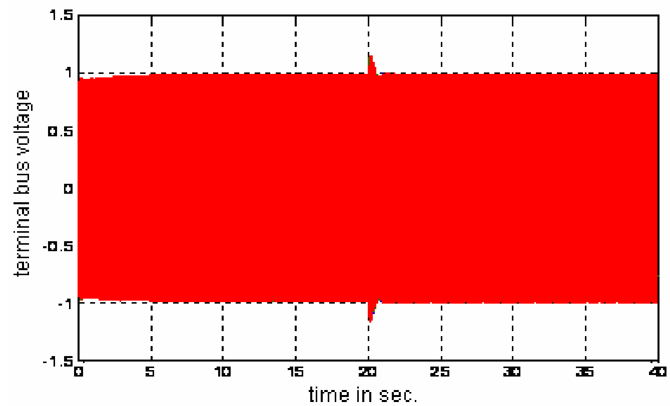

Figure 13. Phase voltage in p.u in grid side of VSWT with DDSG

To see the performance of the system, additional load was added. The VSWT with DDSG system has the capability to supply reactive demand to the power grid and maintained the load voltage at a constant specified level, as shown in Figure 13.

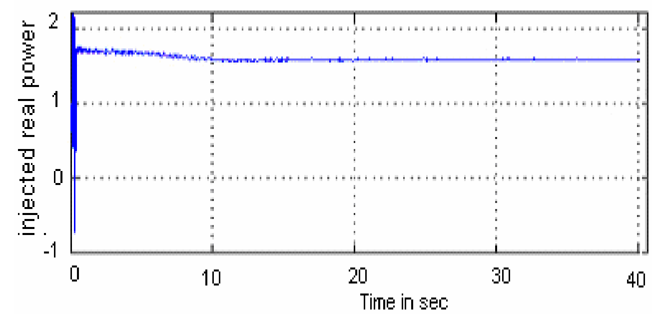

Figure 14. Injected real power 1.5MW in grid side of VSWT with DDSG

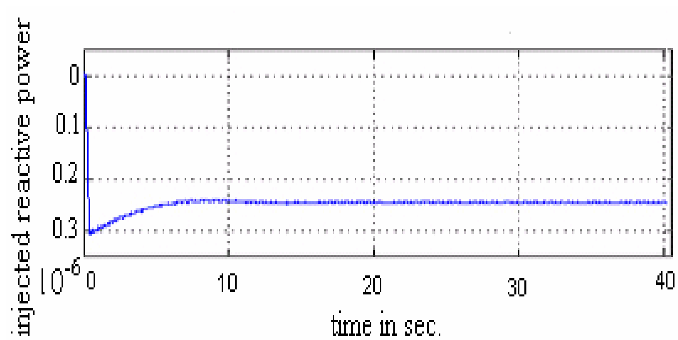

Figure 15. Injected reactive power 0.25MVAR in grid side of VSWT with DDSG

Figure 14 shows the simulation waveform of injected real power 1..5 MW and Figure 15 shows the injected reactive power 0.25MVAR in grid side of VSWT.

IV. CONCLUSION

The modeling of VSWT with DDSG has been implemented in MATLAB/ Simulink. By using function and control blocks provided in the MATLAB software, VSWT is built. Dynamic responses were simulated and analyzed based on the modeled system. A wide scope or a full view of impact studies are necessary before adding wind turbines to real networks. Also, users who intend to install wind turbines in networks must ensure their systems meet the requirements for grid connection. Therefore, this work provides a base for further studies on VSWT capabilities for new power system solutions.

TABLE I. PARAMETERS OF WIND TURBINE MODEL

Rating	1.5MW
Blade radius	38m
Air density	0.55kg/m^3
Rated wind speed	8 m/sec.
Rated speed	2.808 rad/sec.
Cut-in speed	4m/sec.
Cut-out speed	16 m/sec.
Blade pitch angle	4.5^0
Inertia constant of turbine	0.7553 sec.

TABLE II. PARAMETERS OF THE EESG

Rating	1.66MVA
Rated RMS line to neutral voltage	0.69kV
Rated RMS line current	0.8kA
Number of poles	84
Base angular frequency	171.98rad/sec.
Inertia constant of generator	0.3925 sec.

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