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Reactive Power Control of Doubly-Fed Induction Generator Used in Wind Drives

KEYWORDS DFIG, STATCOM, SVC, PCC

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ABSTRACT *It is been observed that an incessant and incredible enhancement of power generation from renewable energy sources is more than from conventional energy sources. The reason for rapid growth of renewable energy sources in the production of electricity arises because they are clean sources of energy, able to be replenished quickly, sustainable and eco-friendly. Since wind is stochastic, variable speed variable pitch-controlled doubly fed induction drives are mostly preferred in wind electric generator. In order to realize the operating characteristics of DFIG, an intensive approach is carried out to simulate it with associated parameters since its performance does not depend upon on the applied stator voltage but also the rotor voltage injected. The magnitude and phase angle of the rotor voltage keeps changing according to the variations of real and reactive power obtained at the rotor side converters. A brief study on analysis, modeling and simulation of DFIG are done using Simulink with the appropriate protection circuits so as to extract optimum power and accurately determine the performance.*

I.INTRODUCTION

Utilization of renewable energy sources is inevitable to meet the rising energy demand as well as to build pollution free environment. Global concern about environmental pollution and continuously increasing energy demand led to the growing interest in developing hybrid power systems.

Since reactive power capability of DFIG is not enough to sustain the required voltage level both at the rotor and grid side converters, flexible ac transmission devices such as STATCOM, the static Synchronous Compensator.SVC at the Point of Common Coupling (PCC)is recommended in order to get voltage regulation.

The control methods include so many but the most popular variable speed variable pitch control wind turbine system prefers only the pitch control mechanism. The major role of this control strategy is to bring forth improved energy conversion efficiency and increased output power quality. It is to orient the turbine blades around its tower in upwind and downwind direction.

This article is being constructed in such a way that the section 2 includes the mathematical modeling of major machinery with components such as DFIG ,power converter and dc link used in wind drives. Section 3 outlines simulation of protection circuits namely STATCOM and SVC using Simulink. The result and conclusion are discussed in section 4.

II.MATHEMATICAL MODELING

During load demands and random wind power input pitch controller is no longer effective and to overcome this problem, an Energy Storage which is able to supply and absorb active power rapidly, has been highly expected as one of the most effective controller of system frequency [1]. The term 'doubly fed' arrives since the voltage to the stator is obtained from the grid and the rotor voltage is injected from power converters. The DFIG consists of wound rotor induction generator with its stator connected to constant frequency three phase grid and rotor windings to grid through a bidirectional back to back ac-dc-ac IGBT voltage source converter. The power converter consists of two converters namely the rotor side converter and grid side converter, active and reactive power controlled by the former while the dc link voltage and hence the terminal voltage of DFIG by the latter is performed. Independent control of rotor excitation voltage which controls the active and reactive power control, high conversion efficiency, reduced cost of converters, less harmonic injection, improved overall efficiency all club together to opt for DFIG for variable speed wind drives. Even the weak power grids in remote places, DFIG can manage the power shortage characterized by low short circuit ratios and under voltage.

For better integration in hybrid power system needs a thorough study of its dynamic behavior, steady state performance, issues like reactive power compensation and voltage control. Fast development of power electronic converters especially the FACTS devices, STATCOM being chosen because of its good dynamic reactive power capability. The voltage fed converter scheme used in wind electric generator is coupled with the shaft of doubly fed induction generator through the speed up gear as in Fig 1.

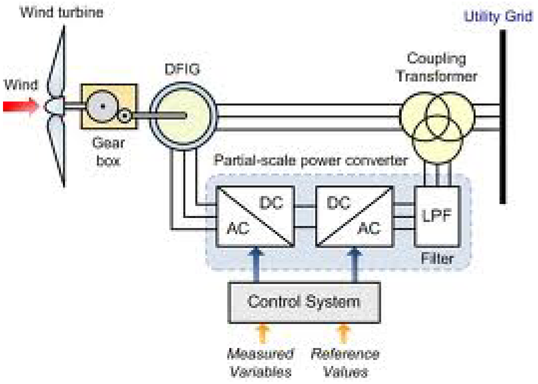

Fig 1.Varible frequency, variable voltage DFIG

The variable frequency variable voltage from the generator is rectified by an IGBT PWM. Mathematical modelings of the following machinery are given as below.

1. Doubly-Fed Induction Generator

The dynamic simulation of DFIG in terms of dq winding is necessary to provide the fast regulation of voltage irrespective of the varying speed of wind profile. High performance drive control methods such as vector or field orient control can be used to get the steady state and transient behavior of the variable speed drive. The dynamic performance of any ac machine is a bit complex since the three phase rotor windings move with respect to the three phase stator windings changes the coupling co-efficient continuously which in turn the rotor flux. With the change in rotor position, changes the time varying inductances makes the machine model complicated.

According to the Park transformation theory, the change of variables namely voltages, currents and flux linkages associated with stator windings of the synchronous machine can be replaced by variables linked with fictitious windings rotating with rotor at synchronous speed, eliminating the time varying inductances[2]. The same theory can be extended to doubly fed induction generators with the stationary as-bs-cs axes at 120° apart, the 3ϕ stationary frame variables are transformed into 2ϕ stationary reference frame first and then to synchronous rotating frame d^e-q^e and vice-versa. Using reference frame theory, the reference signals from a-b-c stationary frame into 0-d-q rotating frame and further by using PI controller the reference signals in 0-d-q rotating frame are controlled to get the desired reference signals for Pulse Width Modulation.

The dynamic modeling of the doubly fed induction generator is represented by synchronously rotating reference frame in dq axis by the following equations.

$$V_{ds} = r_s I_{ds} - \omega_e \psi_{qs} + \frac{d}{dt}\psi_{ds} \qquad (1)$$

$$V_{qs} = r_s I_{qs} + \omega_e \psi_{ds} + \frac{d}{dt}\psi_{qs} \qquad (2)$$

$$V_{dr} = r_r I_{dr} + (\omega_e - \omega_r)\psi_{qr} + \frac{d}{dt}\psi_{dr} \qquad (3)$$

$$V_{qr} = r_r I_{qr} + (\omega_e - \omega_r)\psi_{dr} + \frac{d}{dt}\psi_{qr} \qquad (4)$$

where $V_{ds}, V_{qs}, V_{dr}, V_{qr}$ are the d and q axis stator and rotor voltages respectively. $I_{ds}, I_{qs}, I_{dr}, I_{qr}$ are the d and q axis stator and rotor currents respectively. $\psi_{ds}, \psi_{qs}, \psi_{dr}, \psi_{qr}$ are the d and q axis stator and rotor flues respectively. ω_e is the angular velocity of the synchronously rotating reference frame and ω_r is the angular velocity of the rotor. r_s and r_r are the stator and rotor resistances respectively. The flux linkage equations are given as

$$\psi_{ds} = L_s I_{ds} + L_m I_{dr} \qquad (5)$$

$$\psi_{qs} = L_s I_{qs} + L_m I_{qr} \qquad (6)$$

$$\psi_{dr} = L_m I_{ds} + L_r I_{dr} \qquad (7)$$

$$\psi_{qr} = L_m I_{qs} + L_r I_{qr} \qquad (8)$$

Where L_s, L_r and L_m are the stator, rotor and mutual inductances respectively; with $L_s = L_{ls} + L_m$ and $L_r = L_{lr} + L_m$, L_{ls} being the self or leakage inductance of stator and L_{lr} being the self or leakage inductance of rotor. Solving the aforesaid equations from (5) to (8), the leakage co-efficient σ is found to be

$$\sigma = \frac{L_s L_r - L_m{}^2}{L_s L_r} \qquad (9)$$

All the above equations are applicable to only motors. If the DFIG is operating in generator mode, the current direction is negative and assuming negligible power loss in the resistances of stator and rotor and the active and reactive power from stator and rotor side are given as

$$P_s = -\frac{3}{2}\left[V_{qs} I_{qs} + V_{ds} I_{ds}\right] \qquad (10)$$

$$Q_s = -\frac{3}{2}\left[V_{qs} I_{ds} - V_{ds} I_{qs}\right] \qquad (11)$$

$$P_r = -\frac{3}{2}\left[V_{qr} I_{qr} + V_{dr} I_{dr}\right] \qquad (12)$$

$$Q_r = -\frac{3}{2}\left[V_{qr} I_{dr} - V_{dr} I_{qr}\right] \qquad (13)$$

The total active and reactive power generated by DFIG is given as

$$P_{total} = P_r + P_s \qquad (14)$$

$$Q_{total} = Q_r + Q_s \qquad (15)$$

The total active and reactive power P_{total} and Q_{total} together or any one of the power is positive, the DFIG is supplying power to the grid otherwise it is getting power from the grid.

Again other than the synchronous speed, the rotor tends to experience a torque and the dynamics of rotor is given by

$$\frac{d}{dt}\omega_r = \frac{P}{2J}\left(T_m - T_e - C_f \omega_r\right) \qquad (16)$$

Where P the number of poles of the machine, J the inertia of the rotor, C_f the friction co-efficient, T_m the mechanical torque generated by wind turbine, T_e the electromagnetic torque generated by the machine given as

$$T_e = \frac{3}{2}\left[\psi_q I_d - I_q \psi_d\right] \qquad (17)$$

while positive value of T_e denotes the DFIG is working as a generator. The dynamic model which satisfies the above equations are depicted below as in Fig.2 and Fig.3

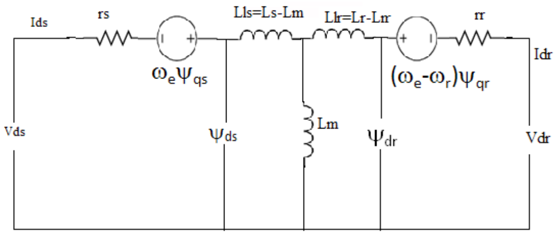

Fig.2 Equivalent Circuit of DFIG at d-axis

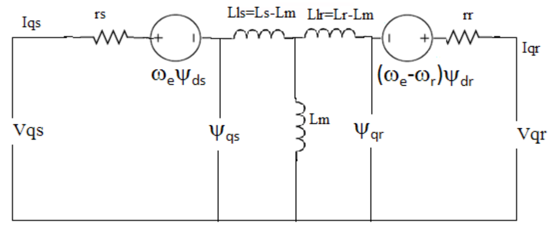

Fig.3 Equivalent Circuit of DFIG at q-axis

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2. Power Converter

The power converter includes both the rotor side converter and grid side converter, back-to back converter connecting the rotor and grid. The rotor end converter acts as a rectifier and grid or front end converter acts as an inverter when the slip power is returned to stator and acts inversely while the slip power is supplied to the rotor. The power rating of both the converter depends on the maximum slip power and the reactive power capability. The grid side converter decides the DC link voltage. Also the transient behavior of the overall hybrid power system can be improved by injecting the large amount of reactive power during fault recovery.

Since a single PWM has an efficiency of 94-98%, the lossless representation is to model the rectifier with this converter. A switch by switch representation of PWM converter with a carrier based sinusoidal pulse width modulation is used to maintain the DC link voltage between the converters.

3. DC Link Voltage

In PWM control method, a fixed dc input voltage is given to the inverter and a controlled ac output voltage is obtained by adjusting the on and off periods of the inverter components. The main advantages of PWM technique are categorize as elimination of lower order harmonics, easy filtration of higher order harmonics and minimal requirement of filtration of unwanted ripples. The DC link voltage can be modeled as a pure capacitor and the dc voltage dynamics for field orientation can be written as

$$CV_{dc}(dV_{DC}/dt) = -P_g - P_s \qquad (18)$$

while C the dc link capacitance, P_g the instantaneous grid power and P_s the load power and V_{dc} and i_c being dc link voltage, capacitor current respectively. For ripple free dc output voltage, LC filter is connected in the DC link. DC link capacitor operates as a solid voltage source and it provides dc isolation between both the converters as in Fig.4.

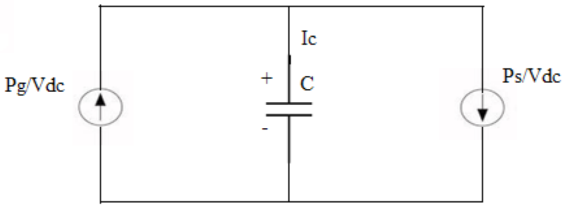

Fig.4 Dynamic equivalent of dc link

Again the amount of energy stored in the dc-link capacitor can be written as

$$E_c = \int P dt = \frac{1}{2} C V_{DC}^{\ 2} \qquad (19)$$

where P is the net power flow into the capacitor, C is the DC-link capacitor value and V_{DC} is the capacitor voltage.

III.REACTIVE POWER CONTROL

The major problems to be solved yet in wind turbines are voltage instability, switching transients, poor response at lower nominal voltages can be tackled by static VAR compensator, switched shunt capacitors and STATCOM which has faster and better performance at reduced voltages rather than SVCs. STATCOMs with a voltage-source IGBT converter are modeled as a controllable energy source. The main reason for using STATCOM is to have flexible power flow control and improved short term voltage stability.

Reactive power (VAR) compensation or control is an essential part in a power system to minimize power transmission losses, to maximize power transmission capability, and to maintain the supply voltage. Flexible AC transmission system (FACTS) devices can supply fast and continuous reactive power [3].Hence it is suggested to use STATCONM and SVC for reactive power compensation to control the magnitude of the voltage at a particular bus bar in any electric power system. The equations governing the reactive power control of HPS in general are listed below.

The change in voltage due to reactive power disturbances is governed by the following equations from (20) to (23).

$$\Delta V(s) = K_V[\Delta Q_{SG}(s) + \Delta Q_{SVC}(s) - \Delta Q_L(s) - \Delta Q_{IG}(s)]/1 + sT_V \qquad (20)$$

$$\Delta Q_{SG}(s) = k_3 \Delta E_q^{'}(s) + k_4 \Delta V(s) \qquad (21)$$

$$\Delta Q_{IG}(s) = k_7 \Delta V(s) + k_6 \Delta PIW(s) \qquad (22)$$

$$\Delta Q_{SVC}(s) = k_8 \Delta W(s) + k_9 \Delta B_{SVC}(s) \qquad (23)$$

The Simulink block diagram for the hybrid power system model for SVC and the corresponding scope are depicted in Fig. 5 and Fig.6

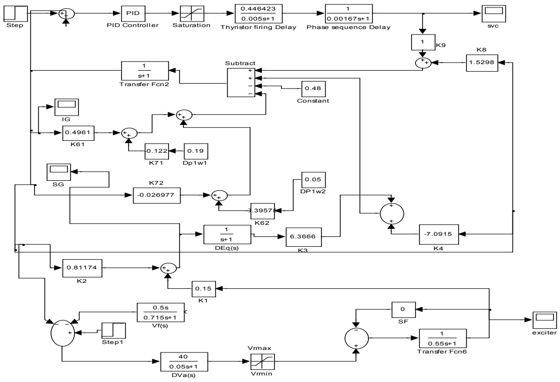

Fig.5 Simulink model of HPS

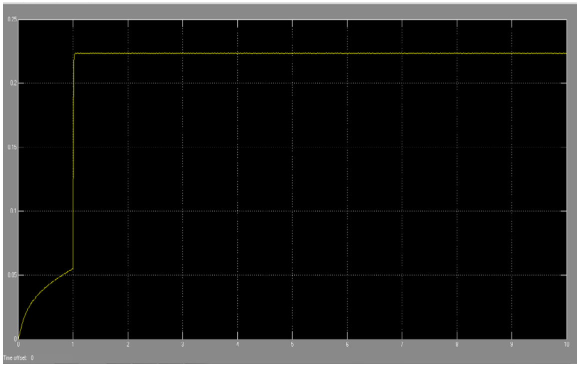

Fig.6 Scope of SVC

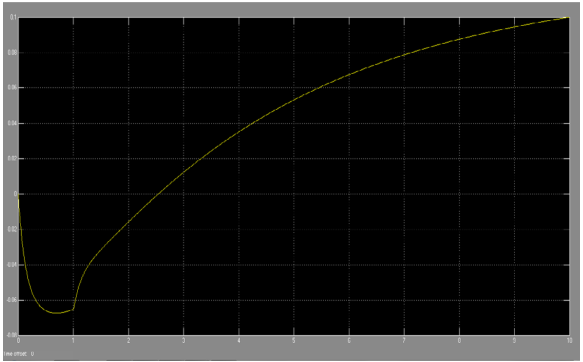

Fig.7 Scope of IG

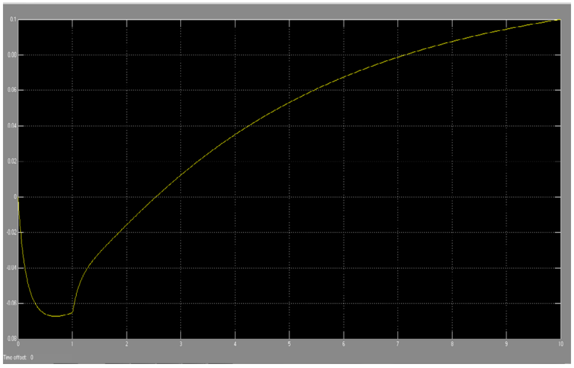

Fig.8 Scope of SG

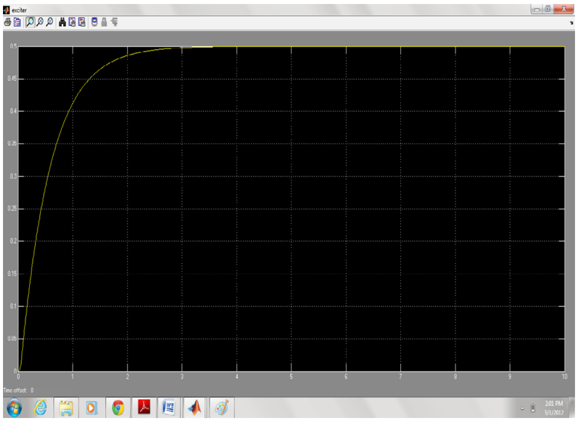

Fig.9 Scope of Exciter

The main parameter considered in HPS model is the reactive power load change which is varied from 0 to 0.2 p.u. with a time span of 0.5 sec to 1 sec. The performance curves of SVC, SG, IG and voltage are shown in Fig.6 to Fig.9. The obtained response curves of ΔQSVC and ΔQSG are more or less similar to each other. The entire study is carried out in the time span 0.5 sec. to 4.5 sec. The reactive power ratings of two induction generators are 0.13 and 0.04 p.u. respectively. Based on the rating of the induction generators, it is better to consider the variation of ΔPIW1 as higher value than ΔPIW2.

Hence, in the study ΔPIW1 is varied from 0.01 to 0.1 p.u. and ΔPIW2 is varied from 0.02 to 0.08 p.u and the reactive power load changes from 0.01 to 1 p.u. are considered. The time domain response specifications such as rise time, settling time, percent over shoot, peak time and steady state value of SVC for above variations are obtained. The percentage of peak overshoot is drastically reduced when ΔQL is varied from 0.5 to 1 p.u. because the maximum reactive power supported by SVC is assumed to be 0.85 p.u. Generally the rise time (tr) increases as ΔQL is varied from 0.01 to 1 p.u. and as it increases in ΔQL and ΔPIW the settling time (ts) decreases.

Secondly the reactive power control of isolated wind-diesel hybrid power system for realistic load disturbance using Simulink has been considered.

Here the diesel Generator set acts as a local grid for the wind energy conversion system and is connected to synchronous generator and wind system on induction generator. The system has a SVC to provide the required reactive power in addition to the reactive power generated by the Synchronous generator. Rather STATCOM employs a voltage source converter (VSC) that internally generates inductive/capacitive reactive power which has the advantages over the SVC scheme [4].

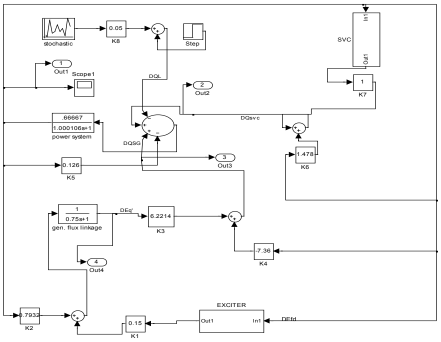

Fig.10.Simulink block of wind-diesel system

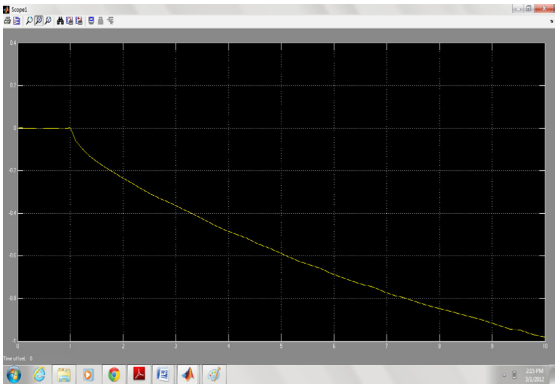

Fig.11 Performance curve for constant slip with stochastic disturbance

It is observed that the first peak of the swings depends upon the type of disturbance allowed. It is also observed that initially the synchronous generator provides the reactive power required by load, but substantially it is met by SVC alone and therefore the steady state value of ΔV, ΔQSG, and ΔQIG becomes zero.

Static Reactive power (VAR) compensation or control is an essential part in a power system to minimize power transmission losses, to maximize power transmission capability, and to maintain the supply voltage.

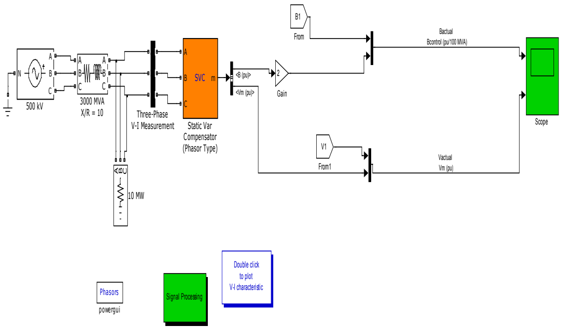

Fig.12. Simulink block of SVC

The SVC response speed depends on the voltage regulator integral gain Ki, proportional gain Kp is set to zero, system strength (reactance Xn), and droop (reactance Xs) [5]. Neglecting the voltage

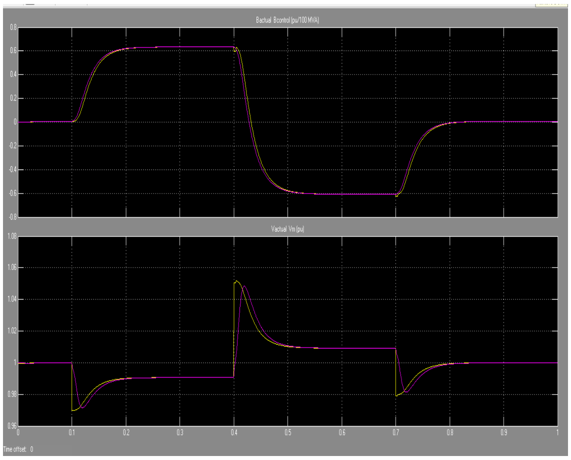

Fig.13.Simulation results

measurement time constant Tm and the average time delay Td, the system can be approximated as a first-order system having a closed-loop time constant.

If the regulator gain is increased or the system strength is decreased, Tm and Td are no longer negligible, an oscillatory response with eventual instability is been observed.

With the efficient usage of STATCOM and appropriate SVC power angle firing, a good reactive power control of the hybrid power system has been obtained

IV.CONCLUSIONS

The disturbance parameters in the model are the change in reactive power of the load (ΔQL), the change in mechanical power input of the induction generator (ΔPIW) and the change in mechanical power input of two induction generators ΔPIW1, ΔPIW2. The performance curves of SVC and STATCOM of the proposed hybrid power system are presented.

The desired dynamic response behavior of the model is studied from the performance curves of the components present in them. Finally all the important time domain response specifications such as settling time, percent over shoot and steady state value of SVC under study are obtained.

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