POWER CONTROL STRATEGY FOR GRID CONNECTED PERMANENT MAGNET SYNCHRONOUS GENERATOR FOR WAVE ENERGY HARNESSING

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Abstract: *This paper describes the operation and control of a variable speed Well's turbine driven permanent magnet synchronous generator connected to the grid by means of fully controlled frequency converter which consist of a PWM rectifier, an intermediate dc circuit and a PWM inverter through a LCL filter. In such systems primary aim is to achieve a low distortion, high power quality power export from the converter with the objective to regulate the power flow or power factor optimization.*
Control schemes are implemented for regulating the dc link voltage for varying input conditions and for regulating the grid current entering the distribution network and hence the power flow into the grid. Response of the system under steady state at balanced/unbalanced, sinusoidal/distorted grid voltage, constant/varying grid frequency and transients such as voltage sag balanced /unbalanced, step variation in input power and under different fault conditions are investigated. In each case the grid current distortion and the dynamic performance of the converter control schemes are evaluated.

Key words: *variable speed permanent magnet generator, PWM converter, power converter controller.*

1. Introduction

Wave power is a relatively young technology unlike the wind power. Waves are generated on the surface of the oceans by the wind which in turn result from the differential heating of the earth's surface. Consequently energy density in water waves is substantially higher than either wind or solar power. This results in a wave power converter being substantially smaller for a given power output compared to wind power converter. The difference between average annual power at deep water sites and that during severe storms is very high. Therefore challenge is to design systems which can economically extract the resource yet service severe extremes. Construction of plant on the shoreline solves this problem but with reduction in the average wave resource [1-3]. Oscillating water column (OWC) are the most popular devices used for wave energy conversion and usually designed as shore mounted. This converts wave energy into low pressure, high volume air flow. This airflow drives a wells turbine which is coupled to the generator [4-6]. Traditionally induction generators are used as they can generate satisfactorily over a reasonable range of speed above synchronous speed. But induction generator depends on an external voltage source to produce magnetic field in the stator which is to say that this device consumes VArs in order to produce watts. On the other hand permanent magnet synchronous generator where the electromagnets of conventional synchronous machine are replaced by permanent magnets are simple and neither requires dc power to create magnetic field as in conventional synchronous machine nor ac power as in induction generator. With the introduction of power electronic interface between the synchronous generator and the grid or the load synchronous generator can be operated at a variable speed. Variable speed operation keeps the turbine at its ideal rotational speed for the best efficiency and reduces peak structural stresses. The output frequency is usually different from 50 Hz. A frequency converter is normally connected to the terminals of generator introducing the extra cost. A full scale IGBT back to back voltage source converter by which the generator is connected to power grid allows the full controllability of the system. Due to the intensified grid codes full scale converter might be favored in

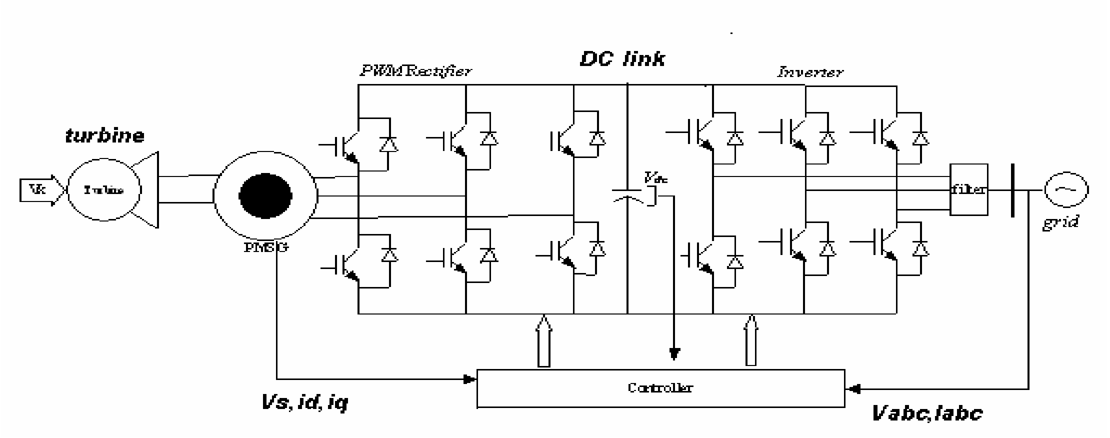

Figure 1 Basic System of study

future in spite of the additional cost incurred. The converter system allows the variable speed operation and there by the speed can be varied over a relatively wide range depending upon the input conditions where the turbine can extract maximum power at different input conditions[7-9]. In case of wind energy system fluctuations in the power fed to the grid occur due to wind velocity changes. In wave energy system axial velocity of air within the OWC varies in accordance with the wave pattern. Additionally there are cyclic variation of air velocity due to bidirectional nature air flow. Hence the control of power fluctuation in a OWC Wave energy scheme is more difficult[5].

In this paper a grid connected wave energy conversion system based on OWC is modeled and controller is designed so that power flow into the grid is regulated in spite of the uncertain disturbances/variations in the input power, grid voltage and frequency disturbances and changes in output power demand. System considered is as shown in Figure 1 consisting of Well's turbine driven permanent magnet synchronous generator connected to the grid by means of fully controlled frequency converter which consist of a PWM rectifier, an intermediate dc circuit and a PWM inverter through a LCL filter.

A comprehensive dynamic model of the entire system is implemented in Matlab Simulink. Control of the system is realized by coordinated control of generator side converter and the grid side converter. Although current and voltage control schemes are possible, current control principle is used for its excellent dynamic characteristics. The criteria for judging the performance of the control schemes are their steady state and dynamic response characteristics, harmonic distortion of the output currents and the quality of power injected to the grid. Both switching frequency effects and the pre existing grid voltage distortion can contribute to poor power quality. The use of LCL filter between the inverter and the grid enhances the performance of the inverter but increases the complexity of the control scheme. LCL filter is a low pass filter which has the potential for improved harmonic performance at low switching frequency which is a significant advantage at high power applications. However the systems incorporating LCL filters are sensitive to grid voltage harmonics due to resonance [9-11]. The scheme used here for regulating the grid current makes use of a synchronous frame PI controller. The reference grid currents in direct and quadrature axis are generated in a reference current calculating block and synchronized to the grid voltage, with active and reactive power references as inputs. Constant stator voltage strategy is used to control the generator side converter such that the dc link voltage is held constant irrespective of the varying input conditions. DC link voltage is controlled through direct axis current controller and ac voltage is controlled through the quadrature axis current controller for the generator side converter[12-15].

2. Modeling of the System

2.1 Modeling of the turbine

The Well's turbine is modeled using MATLAB. The modeling is done based on the equations 1-2 and the characteristics of the turbine.

$$dp = C_a \rho_a b_h l (n/2)(1/a_r)(V_X{}^2 + r\omega_t^2) \qquad (1)$$

$$T_t = C_t \rho_a b_h l (n/2)\ r\left(V_X^2 + r\omega_t^2\right) \quad (2)$$

Where dP is the differential pressure in Pascal, T_t is the gross torque produced by the turbine in Nm, ρ_a is the mass density of air in Kg/m^3, b_h is the blade height of the turbine in m, *l* the blade chord length in m, n is the number of blades of the turbine, r is the average radius of the turbine, a_r the annular area of the rotor in m^2, ω_t is the speed of rotation in rad/s, C_a is the power coefficient and C_t is the torque coefficient. The variation of the power and torque coefficient with the flow rate used in the model are from [5,6]. The flow rate φ_t is defined as in the equation 3.

$$\phi_t = V_x / (r\omega_t) \quad (3)$$

Where V_x *in* m/s is the absolute axial velocity of air in OWC.

2.2 Modeling of the generator

The two axes Permanent magnet synchronous machine stator winding can be considered to have equal turns per phase. The rotor flux can be assumed to be concentrated along d axis while there is no flux along the q axis. Rotor flux is assumed to be constant at a given operating point. If the effect of variations of rotor temperature on the magnet flux is neglected, the rotor voltage equations are not necessary as in the induction machine since there is no external source connected to the rotor. Rotor frame of reference is chosen because the position of rotor magnets determines the instantaneous induced voltage and subsequently the stator currents and the torque of the machine. In the rotor reference frame equivalent q and d axes of the stator winding are transformed into reference frames that are revolving at rotor speed [7]. Rotor magnet axis is the d axis and stator d and q axis windings have fixed phase relationship with the rotor magnet axis. The stator flux linkage equations are

$$V_{qs}^{r} = R_q i_{qs}^{r} + P\lambda_{qs}^{r} + \omega_r \lambda_{ds}^{r} \quad (4)$$

$$V_{ds}^{r} = R_d i_{ds}^{r} + P\lambda_{ds}^{r} - \omega_r \lambda_{qs}^{r} \quad (5)$$

Where R_d and R_q are the direct and quadrature axis winding resistances which are equal.

The q and d axis stator flux linkages in rotor reference frame are

$$\lambda_{qs}^{r} = L_S i_{qs}^{r} + L_m i_{qr}^{r} \quad (6)$$

$$\lambda_{ds}^{r} = L_S i_{ds}^{r} + L_m i_{dr}^{r} \quad (7)$$

In order to compute stator flux linkages in q and d axis the current in the rotor and stator are required. The permanent magnet excitation can be modeled as a constant current source i_{fr} . Since the rotor flux is along the d axis d axis rotor current is i_{fr} and q axis rotor current is zero. Then the flux linkages can be written as

$$\lambda_{qs}^{r} = L_s i_{qs}^{r} \quad (8)$$

$$\lambda_{ds}^{r} = L_S i_{ds}^{r} + L_m i_{fr} \quad (9)$$

Where L_m is the mutual inductance between stator windings and rotor magnets.

The electromagnet torque is given by

$$T_e = \frac{3}{2}\frac{P}{2}\left(\lambda_{ds}^{r} i_{qs}^{r} - \lambda_{qs}^{r} i_{ds}^{r}\right) \quad (10)$$

Electromechanical dynamic equation is given by

$$T_m = J\frac{d\omega_m}{dt} + B\omega_m + T_e \quad (11)$$

Where T_m is the torque of the turbine, T_e is the electromagnetic torque of the permanent magnet synchronous generator, J is the moment of inertia of the system, B is the friction coefficient.

2.3 Modeling of converters

The PWM rectifier and the inverter modeling is implemented using switching function concept [12]. Switching function concept is a powerful tool in understanding and optimizing the performance of static power converters. Using this concept power converter circuits can be modeled according to their function rather than circuit topologies. As this method is not based on the state equation the tedious task of obtaining the state equations is avoided. Also with this model convergence problem is avoided and simulation run time can be reduced. Design parameters such as the voltage, current ratings of the power switches and load currents can easily be calculated. Sinusoidal PWM technique is used for both the rectifier and inverter circuits.

Functional models for the rectifier and the inverter are done based on transfer function theory. According to the transfer function theory for the PWM voltage source inverter input current I_{in} and the output voltages (V_{ab},V_{bc},V_{ca})are dependent variables and input dc voltage V_{dc} and output currents(I_a,I_b,I_c) are independent variables. Relationship between input and output can be expressed as

$$[V_{ab}, V_{bc}, V_{ca}] = (TF)V_{dc} \quad (12)$$

$$I_{in} = (TF)[I_a, I_b, I_c]^T \quad (13)$$

TF is the transfer function of the voltage source inverter and V_{dc} is the dc input voltage to the inverter. TF consist of several switching functions defined by the control strategy used. With sinusoidal pulse width modulation two switching functions are used one for the generation of line to line voltage and the other for the generation of currents within the inverter circuit. The overall model for the inverter consist of sinusoidal pulse width modulating signal generation block, switching function generation block, inverter block, current generating block. Similar concept is used to model the three phase PWM rectifier.

3 Power Converter Controllers

3.1 Generator side converter control

Generator side converter consists of active elements such as IGBTs. This provides best utilization and control of the permanent magnet synchronous generator. Several control strategies have been discussed in the literature namely Maximum torque control, Unity power factor control of the generator and Constant stator voltage control. For maximum torque control stator current is controlled to have q component only in the rotor oriented reference frame. With this strategy reactive power demand of the generator is not zero which increases the converter rating. For unity power factor control d axis current component of the stator is used to compensate the reactive power demand of the generator. Main advantage of this control strategy is that the generator operates at unity power factor which minimizes the converter rating. However there is risk of over voltages due to over speeds since the stator voltage is not directly controlled and stator voltage varies depending upon the speed. The risk of over voltage can be avoided with constant stator voltage control. In this control strategy stator voltage is controlled instead of reactive power, there by stator voltage is limited to the rated value. Control is done in stator voltage oriented reference frame where d axis is aligned to the stator voltage vector.

Then Active power depends on direct axis stator current and the reactive power depends on the quadrature axis stator current. Active and reactive powers are given by

$$P_s = \frac{3}{2} \quad V_{ds}^{s} i_{ds}^{s}$$

$$Q_s = -\frac{3}{2} \quad V_{qs}^{s} i_{qs}^{s} \tag{14}$$

Where V_{ds} and V_{qs} are the direct and quadrature axis components of stator voltages and i_{ds} and i_{qs} are the direct and quadrature axis currents of the stator current. Direct axis stator current component i_{ds} is determined by active power production of generator and quadrature axis stator current component i_{qs} can be used to control stator voltage to its rated value. With this control both generator and converter always operate at rated values for which they are designed. But the converter rating increases with the reactive power demand of the generator.

So as to ensure that the active power generated is fed to the grid via the dc link, dc link voltage must be kept constant. Assuming a loss less converter

$$P_s = V_{dc} I_{dc} = \frac{3}{2} v_{ds} i_{ds} \tag{15}$$

Where V_{dc} is the dc link voltage and I_{dc} is the output current of the generator side converter. Above expression indicates that dc link voltage as well as active power can be controlled using i_{ds}. Stator voltage control is achieved through i_{qs} . Block diagram of the control scheme is shown in Figure 2.

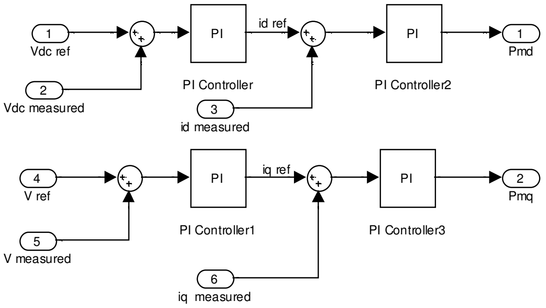

Figure 2 Schematic for DC link voltage control

Control scheme has fast responding inner current loop controlling d axis and q axis stator currents and outer slower loop for controlling dc link voltage and stator voltage. Inner control loops provide control signals in d and q axis namely P_{md} and P_{mq} which are given to PWM power converter.[8,9].

3.2 Grid side converter control

Main objective of the control scheme is to modulate the inverter to regulate the magnitude and phase angle of the grid supply current so that the real and the reactive power entering the network can be controlled [13,15]. LCL filter and the grid are modeled based on the system equations. The measured three phase ac currents are transformed into dc components in a synchronously rotating frame so that the steady state error that is normally associated with the application of PI control to ac quantities can be eliminated. Also this has the advantage of controlling the real and reactive power independently. The reference grid currents in the direct and quadrature axis are obtained from the active and reactive power reference set points. The generation of reference currents needs to be synchronized to the grid voltage. The active and reactive power references in terms of direct and quadrature axis currents is given by

$$\mathrm{P}_{\mathrm{ref}} = \frac{3}{2}\left(v_{gd}\, i_{gdref} + v_{gq}\, i_{gqref}\right) \tag{16}$$

$$\mathrm{Q}_{\mathrm{ref}} = \frac{3}{2}\left(v_{gq}\, i_{gdref} - v_{gd}\, i_{gqref}\right) \tag{17}$$

The reference currents for the direct and quadrature axis currents can be derived from equation (16-17) as given by equation (18-19).

$$i_{gdref} = \frac{2}{3}\frac{(P_{ref}V_{gd} + Q_{ref}V_{gq})}{(V_{gd}^{\;2} + V_{gq}^{\;2})} \tag{18}$$

$$i_{gqref} = \frac{2}{3}\frac{(P_{ref}V_{gq} - Q_{ref}V_{gd})}{(V_{gd}^{\;2} + V_{gq}^{\;2})} \tag{19}$$

Where V_{gd} and V_{gq} are the direct and quadrature axis components of the grid voltage. These calculations are performed in reference current calculating block.

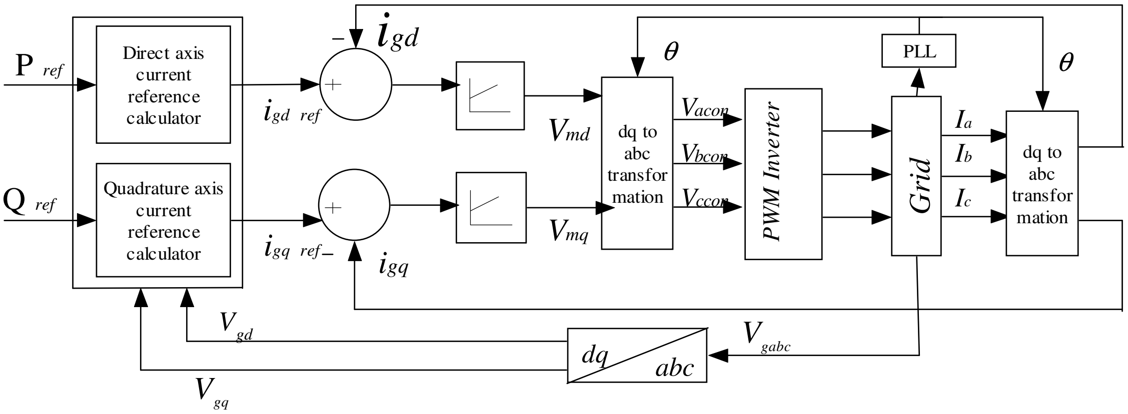

Figure 3 Block diagram of PI current control scheme for a grid connected VSI.

Figure 3 shows the control strategy used for the generation of reference currents and PI control scheme for the control of active and reactive power flow into the grid. The controller is equipped with current controllers. Active power control is possible through the d axis component of grid current and the reactive power control through the q axis component of grid current. The d and q axis reference currents are calculated as per the equation (18-19) in the calculating blocks. The three phase grid currents i_a, i_b, i_c are sensed and transformed to dq0 reference frame rotating at electrical frequency of grid voltage. Synchronization of the reference frame to the grid voltage is achieved by PLL method. The control voltages for the three phase VSI are generated based on the errors in d axis and q axis currents through PI controllers. The PI controllers produce the control voltages for the inverter in d and q axis based on the following equations(20).

$$\begin{aligned} V_{md} &= K_{Ph} i_h + K_{ih}\int i_h dt \\ V_{mq} &= K_{Pj} i_j + K_{ij}\int i_j dt \end{aligned} \tag{20}$$

where i_h and i_j are the errors in d axis and q axis grid currents, K_{ph} , K_{pj} are the proportional and K_{ih}, K_{ij} are the integral gains of the PI controllers. The voltage V_{md}, V_{mq} are then transformed into a b c coordinates to get control voltages V_{acon}, V_{bcon}, V_{ccon} for the PWM inverter. Reference power for the active power can be obtained through a maximum power tracking characteristic, however model has the option of setting it at any suitable value. Reference power for the reactive power is obtained through a voltage controller which will enable the unity power factor operation or can be set at any desired value.

4 Simulation and performance evaluation:

In order to evaluate the performance of the control scheme the model is examined under various conditions. These conditions include steady state, dynamic conditions and transients such as grid voltage disturbances, variations in the input power and fault conditions. In each case the grid current distortion is evaluated and system performance is analyzed. DC link voltage is maintained constant at 800 V, minimum value of dc reference voltage is determined by the inverter output voltage as

$$V_{dcref} = 2\sqrt{2/3}\,V_{gline} \qquad (21)$$

Where $V_{g,\text{line}}$ is the line to line voltage at the inverter output. The inverter is connected to a 440 V LV grid through a LCL filter, hence the output of the inverter is taken 10% more than the grid voltage for the calculation of the reference for the dc link voltage. Figure 4 shows the response of the active and reactive powers following closely the respective references values. Here the input to the turbine is maintained fixed and active and reactive power references are set initially at 15kW and 5 kVAr respectively. Once the steady state is reached the references for active and reactive powers are changed to 25 kW and 10kVAr respectively.

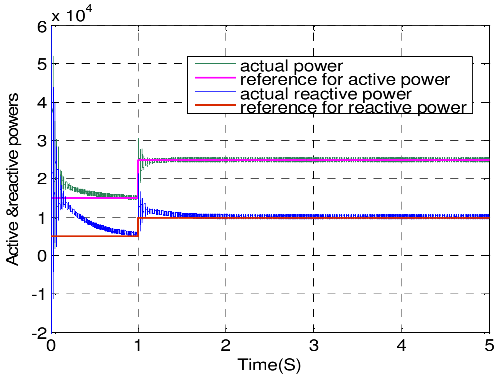

Figure 4 Active and reactive power response

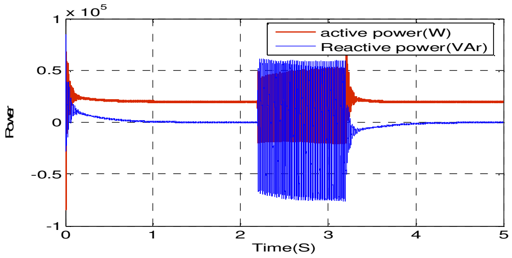

Figure 5 Active and reactive power response under single line to ground fault condition.

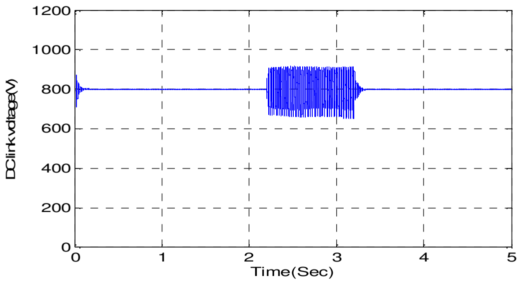

Figure 6 Effect of phase to single line to ground fault on the dc link voltage

Figure 5 shows the active and reactive power responses under single line to ground fault. Fault occurs at t=2.2s and cleared at t=3.2 sec. Active power reference is set at 20kW and the reactive power reference is set at zero. During the fault, distortion in the grid current is high and therefore distortions are seen in the active and reactive power. When the fault is cleared the active and the reactive powers follow the respective references. Figure 6 illustrates the effect of single line to ground fault on the dc link voltage. It is observed that with a symmetrical step increase of grid voltage by 20% THD of the grid current increases from 2.3% to 4.16%. This is due to increase in all the harmonic components with significant increase in the third harmonic component. Figure 7 shows the active and reactive power responses under symmetrical grid voltage dip of 20%. Distortion in grid voltage imposed at t=2.2 and cleared at t=3.2 sec. Active power reference is set at 20kW and the reactive power reference is set at zero.

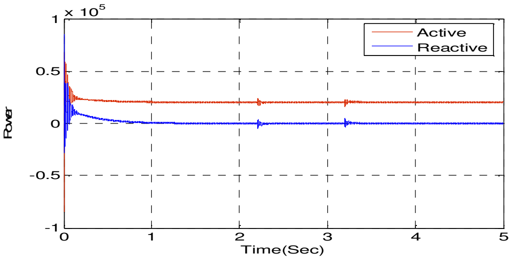

Figure 7 Response under Distorted grid voltage:

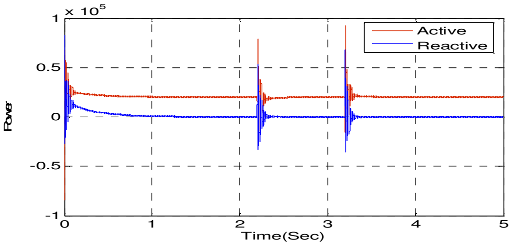

Figure 8 Response when frequency decreased by 4%

Figure 8 demonstrates the effect of change in the frequency of the grid voltage. A symmetrical dip of frequency by 4% is applied during t=2.2 to 3.2 sec. THD of grid current which was 2.4% jumps to about 12%.

In case of wave energy with both wave height and wave period varying over a range, axial velocity and hence the power extraction from the waves varies from instant to instant in every wave cycle. In addition to statistical variation of air speed due to statistical variations of wave there is cyclical variation of air velocity due to bidirectional nature of air flow which is rectified by the Well's turbine and hence unidirectional torque is produced. Therefore axial velocity of air swings from zero to a maximum value and back to zero in a period of typically 4 -5 sec in a periodically repeated manner. For this reason model is applied with varying axial velocity as shown in figure10. The response of the controller is given in figure11,12. Power generated by the generator varies in accordance with variations in the axial velocity, but the controller maintains the power fed to the grid at the reference value and the reactive power at zero as shown in figure 11. Figure 12 shows the dc link voltage for varying axial velocity .

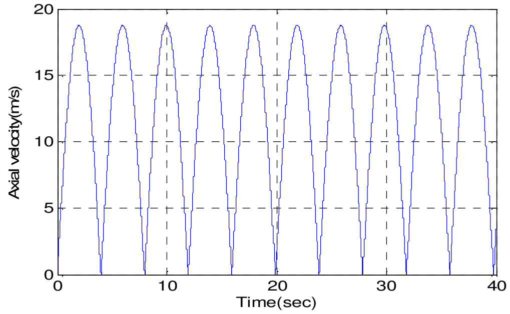

Figure 10 Varying axial velocity

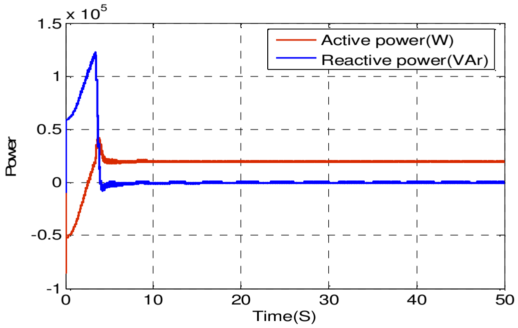

Figure 11 Active and reactive power flow into the grid under varying input condition

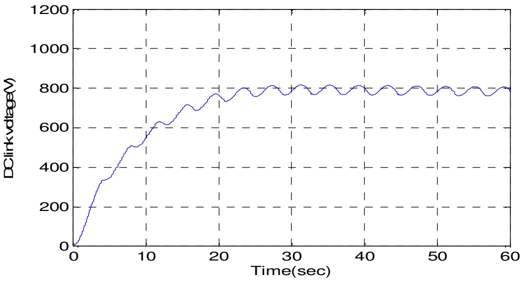

Figure 12 DC link voltage with varying axial velocity

4.1 Response of the controller with actual wave data

To evaluate the performance of the controller for actual wave input the model is applied with the actual wave data obtained from the Indian wave energy plant. Figure 13 shows the spectral energy density of the wave pattern given as input to the OWC turbine model. This wave pattern has a significant wave height of 1.0050 m, period of 16.7333sec and peak angular frequency of 0.6545rad/sec.

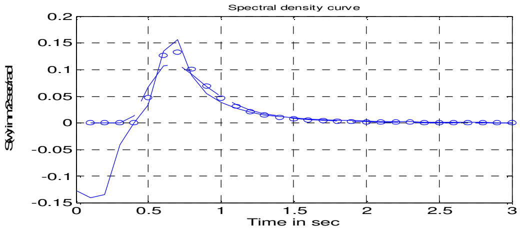

Figure 13 Spectral energy density curve

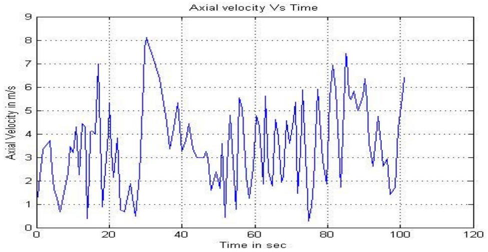

Figure 14 Axial velocity within OWC

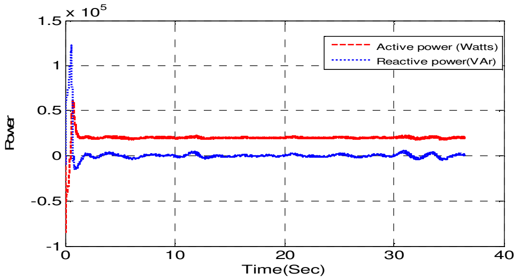

Figure 15 Active and Reactive power flow into the grid

With this input the axial velocity within the water column varies in accordance with the wave pattern shown in figure 14. Figure 15 the active and reactive power fed to the grid both are maintained at the set value irrespective of the variation in the power generated. This illustrates that the controller gives good response for the real wave data input .

5 Conclusions

In this paper a dynamic model for the representation of a variable speed Well's turbine driven permanent magnet synchronous generator connected to the grid by means of fully controlled frequency converter is developed.

Steady state and dynamic response of the system has been evaluated for various conditions. The results under different operating conditions show that the control scheme provides a good response. Under unsymmetrical unbalance of the grid voltage and under fault conditions the distortion in the output current increases significantly. The proposed model provides adequate accuracy under steady state and transient conditions and it is efficient with regard to the calculation time.

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