ADCONIP
2014
Hiroshima

Controlled Power Point Tracking for Power Balancing in PMSG based Wind Energy Conversion System

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Abstract: With the increasing penetration of wind energy into power system, wind energy conversion systems (WECSs) should be able to control the power flow for limited as well as maximum power point tracking. In contrast to the traditional pitch angle control, this paper focusses on field oriented speed control of permanent magnet synchronous generator (PMSG) for controlling the active power flow based on the wind turbine characteristics. In this paper a back to back AC/DC/AC topology is implemented for interfacing the WECS to the distribution network with various power electronic interfaces providing the necessary control over the power flow. The proposed control strategy can provide power balancing and reserve capacity without use of expensive energy storage devices like batteries. Simulations are carried out under varying load demand as well as changing weather conditions to demonstrate the applicability and effectiveness of the proposed control strategy.

Keywords: Permanent Magnet Synchronous Generator (PMSG), Wind Energy, Power balancing, Speed control, Field oriented control, Hysteresis control .

1. INTRODUCTION

With growing energy demand and climate change concerns, it is increasingly becoming clearer that dependency on conventional energy sources, particularly fossil fuel based sources must be reduced gradually. Alternative/ renewable sources are going to play a vital role in reducing the energy deficit for re-emerging nations. Installed capacity of various renewable sources of energy such as solar, wind, tidal etc. is increasing rapidly and steadily. Integrating these systems with conventional grid has posed many challenges, such as, synchronization, effect on harmonic interactions, effect on power quality, aspects related to control and system stability, co-ordination over large spatial distances, etc. Wind energy is the most preferred renewable energy source around coastal regions and it can be installed onshore or offshore. Wind farms have capability to produce large amounts of power (typically of the order of MW-GW's of power). Both standalone and grid connected wind energy conversion systems (WECS) are being used.

Most of the present WECSs use maximum power point tracking control strategies to extract maximum power available from wind. A large number of maximum power point control strategies (Thongman & Ouhrouche, 2003; Abdullah et al. 2012) have been proposed in the literature e.g. tip speed ratio control, power signal feedback control, pitch/stall control etc. All these control strategies try to extract maximum power all the time. However for a standalone or distribution generation system, there may be situations when WECSs are not supposed to generate maximum power (Orlando et al., 2009). With standalone generation systems, it is important that excess power coming from WECS is dissipated or stored somewhere to keep whole system stable and in operation. Further, for distributed generation system, it is important that each generation unit has some reserve power capacity. Such reserve power capacity ensures reliable and stable power system in presence of sudden spikes in power demand. Extracting maximum power all the time makes the system vulnerable to sudden climatic changes and can cause problems such as DC link voltage collapse or sudden reduction in power output (Libo et al. 2007). While WECS is widely recognized, controlled power extraction has thus far not received significant attention and, thus only maximum power point tracking (MPPT) is used in WECS (Alizadeh & Yazdani, 2013). Some limited power point tracking techniques based on sliding mode control (Qi et al., 2013) and fuzzy logic control (Qung et al. 2011) have been proposed. These techniques rely on energy storage systems such as batteries. However, renewable energy systems that are interfaced with the help of batteries to standalone or grid connected network, have following disadvantages: i) it makes the entire system costly, ii) they also require continuous maintenance/ replacement (batteries) and iii) it makes the system vulnerable to climatic changes (Bhugra & Detroja, 2013). Thus controlled or limited power point tracking in WECS without any energy storage devices is very important and also the main focus of this paper.

In this paper, a control strategy for extracting limited power from WECSs is proposed to eliminate the use of batteries or any other expensive storage devices. In the proposed approach controlled/ limited power point tracking is achieved based on wind turbine characteristic curve and field oriented speed control of permanent magnet synchronous generator (PMSG). The choice is based on the expectation that PMSG based WECSs will be widely deployed in future due to their low loss generators, low maintenance requirement and quiet drive trains (Soderlund & Ericsson, 1996). The proposed control strategy involves operating in two modes of operation: i) sufficient power condition and ii) insufficient power condition. For a given wind speed, if the power requirement is lower than the WECS capacity then the system operates under limited power point tracking i.e. the amount of power generated will be just enough to meet the load demand. On the other hand, if the load demand is higher than what WECS system can generate then the system works in MPPT mode. The proposed control strategy can be used in situations where there are constraints over the power supplied by the grid, e.g. rating of distribution transformer may determine how much power can be drawn to/ from the grid and also provides reserve capacity to WECS. The main advantage of having reserve capacity to the system is that having reserve capacity facilitates stable operation of the system as it can deal with sudden changes in power demand and climate conditions. The proposed control technique can be used for both types, i.e. standalone and grid-connected WECS. Similarly, the proposed control strategy can also be used for reactive power compensation as it has been shown that the VSI (Voltage Source Inverter) or Current Source Inverter(CSI) can be used to control active and reactive power flow through inverter (Dasgupta et al., 2011). Simulations were carried out to demonstrate effectiveness of the proposed control strategy under varying load demand as well as varying climate conditions.

The remainder of the paper is organized as follows: the system under consideration is described in section 2, followed by system model description in section 3. The proposed LPP technique is derived in section 4. Section 5 describes the simulation results and section 6 ends with some concluding remarks.

2. SYSTEM OVERVIEW

In this paper, a WECS with peak power capacity of 30kW is interfaced with the three phase three wire grid with a shunt connected local load network. A back to back AC/DC/AC topology is implemented for interfacing the WECS to the distribution network as shown in Figure 1. The first stage consists of a controlled rectifier .The main objective of power balancing is achieved through the vector control technique of this controlled rectifier. The controlled rectifier operates in two operating region i) when WECS output power is sufficient to supply the total load demand and, ii) when WECS output power is insufficient to supply the load demand and the WECS is at maximum power point. The control technique used for the controlled rectifier to operate in both the regions is speed control of PMSG through vector control. The reference point for speed of rotor (w_r^*) is obtained based on the characteristics of wind turbine i.e. speed tip ratio (λ), Power coefficient of wind turbine (C_P) and the load demand at consumer site. A three-leg two-level VSI is used for transferring power from WECS to the point of common coupling (PCC) and to meet the reactive power requirement, if any. CSI can also be used with the proposed control technique and it will not affect the system as both the proposed control technique for controlled rectifier and the current control of inverter are independent of each other. Three Inductors are used to interface the inverter with the grid. The WECS system parameters and Wind Turbine Parameters are given in Table 1 & Table 2.

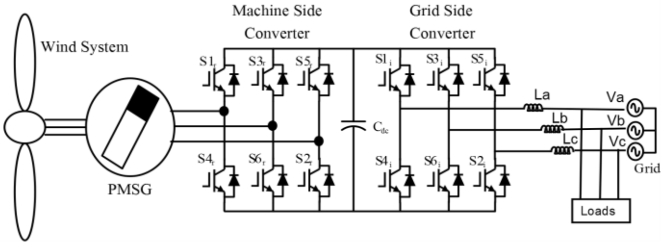


Figure 1: WECS System Configuration

Table 1: WEC system Parameters

C_{dc} (dc link capacitance)	6000 µF
L_{inf} (interfacing inductance)	10 mH
V_{ll} (line to line grid voltage)	415V

Table 2: Wind turbine Parameters

Performance Parameters	
Rated Electrical Power	29 kW
Wind speed cut- in	3 m/sec
Rated wind speed	10 m/sec
Rotor Parameters	
Type of Hub	Fixed Pitch
Rotor Diameter	15 m
Swept Area	177 m^2
Rotor Speed@ rated wind	100 rpm
Generator Parameters	
Type	3 phase/6 pole synchronous
Voltage	680 V
kW @ Rated wind speed	30 kW
Speed RPM nominal	3000 rpm
Transmission Parameters	
Ratio	1 to 30 (rotor to gen speed)

3. SYSTEM MODELING

3.1 Modeling of wind turbine with PMSG

Wind turbines cannot fully capture wind energy. The wind turbine model is based on three general equations (Errami Y. et al., 2011):

1. The extracted aero dynamical power (1)
2. The turbine power coefficient C_P (2)
3. The tip speed ratio λ (3)

The model has three inputs: the wind speed, the pitch angle and the rotor speed

$$P_{wind} = \frac{1}{2}\rho A v_w^3 C_p(\lambda,\beta) \qquad (1)$$

$$C_p = a_1\left(\frac{a_2}{\lambda_i} - a_3\beta - a_4\right)e^{-\frac{a_5}{\lambda_i}} \qquad (2)$$

where, $$\lambda_i = \frac{1}{\frac{1}{\lambda - 0.02\beta} - \frac{0.003}{\beta^3 + 1}}$$

$$\lambda = \frac{w_r R}{v_w} \tag{3}$$

where ρ is the air density is equal to 1.225 kg/m^2, A is the area swept by the blade, v_w is the wind speed and C_P is the power coefficient which depends on the tip speed ratio λ and β is the pitch angle, R radius of the blade. Variation of C_P with respect to the tip speed ratio λ, keeping pitch angle β=0, is shown Figure 2.

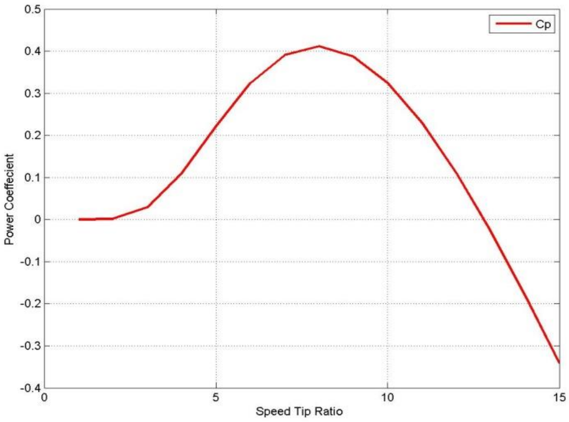


Figure 2: C_p (Power Coefficient) Vs λ (Tip Speed Ratio)

It can be observed from the Fig 2 that Power extracted by any wind turbine from the wind energy is the only 41% of the maximum energy available from the wind normally. For the aim of this study the pitch angle is kept to 0 as no pitch angle control is considered in this study of work.

The rotor speed input is connected to the one mass mechanical drive train model computing the turbine rotor swing. The equation is (Kanellos & Hatziargyriou, 2008) :

$$\left(J_T + J_G\right)\frac{dw_g}{dt} = T_T - T_G - Dw_g \tag{4}$$

where, J_T and J_G are the turbine and generator moment of inertia, T_T and T_G are the turbine and electromagnetic torque, D is the viscous friction factor and w_g is the generator rotor speed.

3.2 PMSG model

Dynamic modeling of PMSG can be described in d-q reference system as follows (Kanellos & Hatziargyriou, 2008) :

$$\frac{di_q}{dt} = -\frac{r_s}{L}i_q - w_e i_d + \frac{w_e \Phi_m}{L} - \frac{V_{gq}}{L} \tag{5}$$

$$\frac{di_d}{dt} = -\frac{r_s}{L}i_d + w_e i_q - \frac{V_{gd}}{L} \tag{6}$$

$$w_e = p w_g \tag{7}$$

$$T_e = -\frac{3}{2}p\Phi_m i_q \tag{8}$$

where, r_s is the stator resistance, L is the inductance of the generator on the d and q axis which are taken to be equal, Φ_m is the permanent magnetic flux and w_e is the electrical rotating speed of the generator defined by (7) and p are the number of pole pairs. In order to complete the modeling of PMSG the output electromagnetic torque T_e can be described by (8) when direct axis current i_d is kept zero.

4. CONTROL STRUCTURE

The overall control structure of the proposed power balancing control strategy is shown in Figure 3. The entire control system is divided into three parts: i) Limited Power Point Tracking (LPPT) Control of PMSG using vector control technique for controlled rectifier, ii) DC-link Voltage control and iii) inverter current control. In the following subsections, each of these control system is explained in detail.

4.1 Limited power point control

The proposed control technique is based on the characteristic curve between the C_P and λ shown in Figure 2 for obtaining the required reference speed of the rotor based on the load demand. We will be operating the controller on the left hand side of the characteristics curve of C_P and λ because if we operate it on the right hand side of the curve, speed of the rotor may increase more than the rated speed of generator thereby increasing the mechanical stresses on the generator. The mathematical relation between P_{ref}(Power Reference/Load Demand) and w_{ref} (speed of the rotor) required to generate that much Load demand P_{ref} are given by following equations:

$$C_{pref} = \frac{P_{ref}}{P_{\max}} \tag{9}$$

$$\lambda_{ref} = 12.28C_p + 2.5 \tag{10}$$

$$w^*_{ref} = \frac{\lambda_{ref} v_w}{R} \tag{11}$$

$$P_{\max} = 0.5\rho A v_w^3 \tag{12}$$

where, C_{pref} in equation (9) gives the desired power coefficient for the wind turbine based on the load demand (P_{ref}). Equation (10) is obtained by approximating the left hand side of the curve to approximately a linear straight line and adding an offset to compensate for the linear approximation of the curve. The desired reference speed then can be obtained from the relation given by equation (11).

4.2 Speed control of PMSG

Field oriented control strategy is implemented in the synchronous rotating reference frame for an easier control. The control strategy requires three controllers, two for the currents in the inner loop and one for the outer loop. An important requirement is that the current controllers must react faster on the input variations than the speed controller. The field oriented Control schematic block is represented in Figure 4.

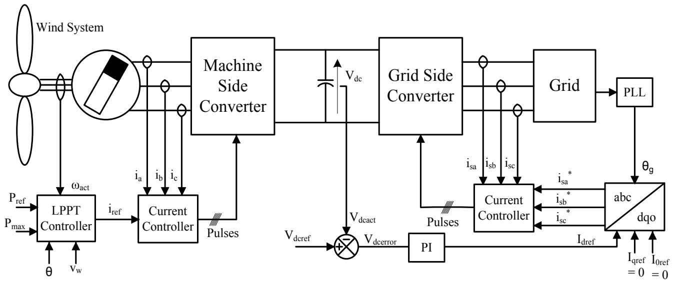


Figure 3: Overall control system structure

For implementing the proposed control strategy shown in Figure 4, the acquisition of the two phase stator currents, the DC link voltage and the rotor position are required. The speed of the rotor w_g can be measured through the speed sensors which can then be integrated to obtain rotor position. Knowing the rotor position Θ_g the park coordinate transformation is applied to the current references i_{sqref}, i_{sdref} thus obtaining $i_{sa}^*, i_{sb}^*, i_{sc}^*$ references in stationary reference frame coordinates.

Hysteresis current controller is used to generate the PWM (Pulse Width Modulation) signals. The reference values thus obtained from the speed PI controller of the outer loop in stationary reference frames are subtracted from the instantaneous values of individual phase currents i_{sa}, i_{sb}, i_{sc} and then given to hysteresis controllers operating with a band limit of (-0.1A & 0.1A). The output of this hysteresis controller is then given to relays, which will finally give the switching signals for rectifier circuit. The controller parameters as obtained by trial and error are given in Table 3

Table 3: LPPT controller parameters

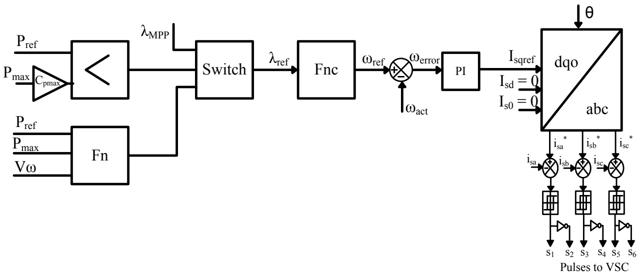
C_{pmax}	0.41
K_P	12
K_I	0.234
Band limit for Hysteresis control	-0.1 to 0.1

4.3 DC Link voltage controller

For satisfactory operation of the inverter, the DC-link voltage should be maintained at a suitable voltage level which is given by the following (Kanellos F.D. and Hatziargyriou N.D. 2008)

$$V_{dc}^* = \frac{2\sqrt{2}V_{ll}}{\sqrt{3}m} \tag{13}$$

where V_{ll} is the line to line voltage of the grid, and m is the modulation index. For the system parameters considered in this paper, the voltage should be maintained at 700V. In order to maintain this voltage level a PI controller is used in the Figure 3. Reference DC link voltage (V_{dc}^*) is compared with actual DC-Link voltage (V_{dc}) and the error signal is given to the PI controller. The output of the PI controller determines current references (I_d^*) for the VSI.



* Fn is equation-(10)

*Fnc is equation-(11)

Figure 4: Proposed LPPT controller

4.4 Inverter controller

Hysteresis current control technique is used to control the power flow through the inverter. The output from the PI controller of DC-link Voltage controller is used to calculate the d-q frame current reference (I_d^*). The final I_d^* obtained from equation (14) and I_q^*=0 which are in dq0 reference frame (synchronous reference frame) are converted into abc frame (stationary reference frame) using PLL (Phase Locked Loop) (15).

$$I_d^* = K_p \Delta V_{dc} + K_i \int \Delta V_{dc} dt \tag{14}$$

$$\begin{bmatrix} I_d^* \\ I_q^* \\ I_0^* \end{bmatrix} = \frac{3}{2} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\Pi}{3}) & \cos(\theta + \frac{2\Pi}{3}) \\ -\sin(\theta) & -\sin(\theta + \frac{2\Pi}{3}) & -\sin(\theta + \frac{2\Pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} I_{sa}^* \\ I_{sb}^* \\ I_{sc}^* \end{bmatrix} \tag{15}$$

The PLL synchronizes the inverter voltage with the grid voltage .The reference values thus obtained in stationary reference frame are subtracted from the instantaneous values of individual phase currents i_{ga}, i_{gb}, i_{gc}, and then given to hysteresis controllers operating with a band limit of (-0.1A & 0.1 A). The output of this Hysteresis controller is then given to relays, which will finally give the switching signals for rectifier circuit. The controller Parameters as obtained by trial and error are given in Table 4.

Table 4: DC link voltage and hysteresis controller parameters

K_V	0.0014
K_P	2
K_I	0.1
Band limit for Hysteresis control	-0.1 to 0.1

5. SIMULATION AND RESULTS

The proposed wind energy conversion system was designed and modelled in MATLAB Simulink using Simpowersystem blocks. To demonstrate effectiveness and applicability of the proposed control strategy, simulations were carried out for various modes of operation. The simulation cases considered here are chosen to demonstrate the usefulness of the proposed control algorithm under varying load demand as well as varying climate conditions.

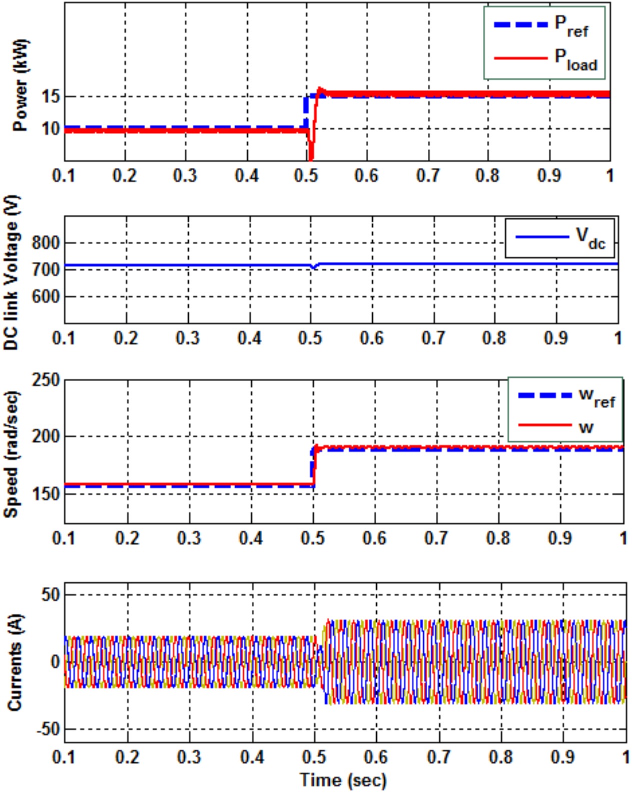


Figure: 5 Response to a step change in load demand

Case 1: Sudden change in load demand

First, simulations were carried out for variable load demand during power sufficient mode. Initially the WECS system was operating under steady state condition with load demand (P_{ref}) of 10 kW when wind speed is 9 m/sec .At this wind speed the WECS can generate a maximum power (P_{max}) of 29 kW, indicating that the proposed control technique will be operating in power sufficient mode. At time t=0.5 sec, a step change from 10 kW to 15 kW in P_{ref} is given.

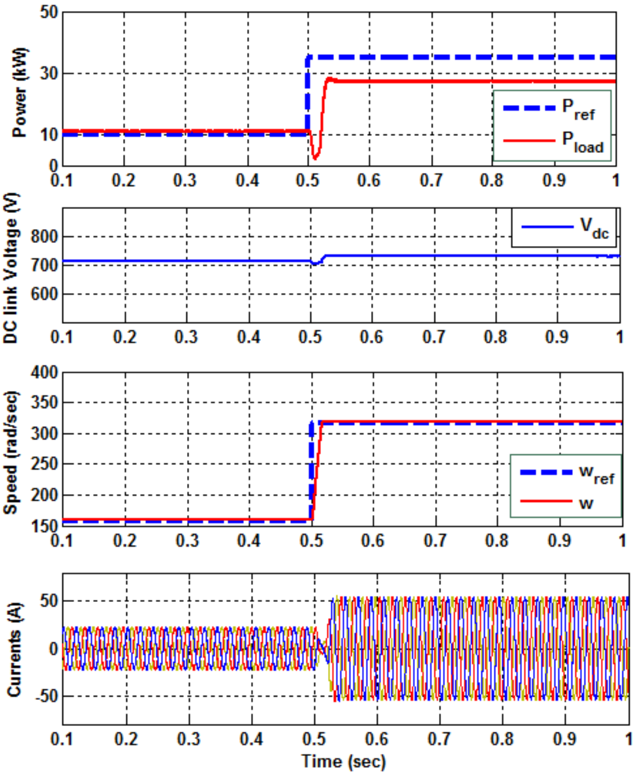


Figure:6 Operation under insufficient power condition

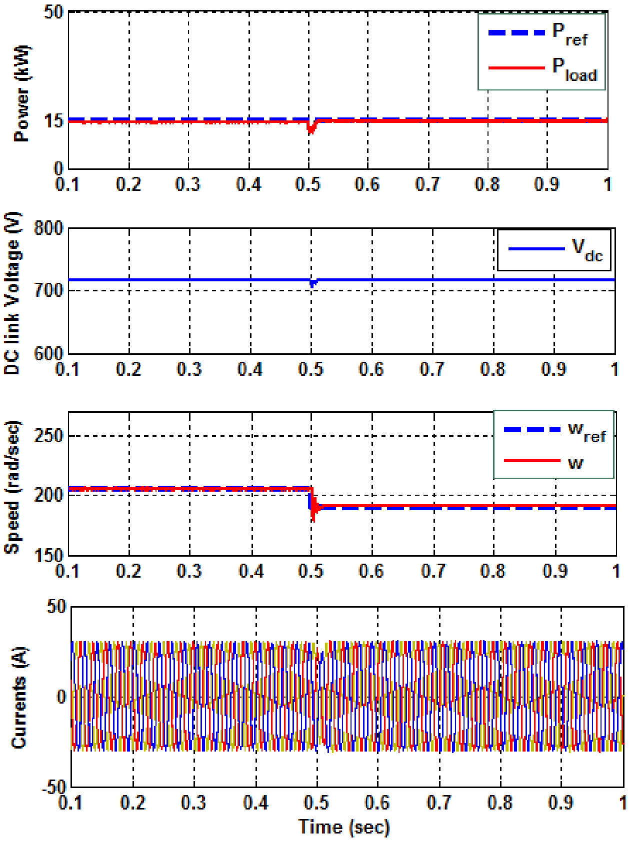


Figure:7 Operation under sudden climate change condition

Simulation results pertaining to the power delivered to the load (P_{load}), (V_{dc}) dc link voltage, (w_{ref}) reference speed of generator in rads/sec, (w) actual speed of the generator, and inverter output current (Currents) waveforms are shown in Figure 5. It can be observed from the waveforms that the proposed controller responds very quickly to the set point changes and hence achieves power balance.

Case 2: Operation in MPPT mode

Next, the proposed controller's response to the power insufficient case is simulated. As in case 1, the system was initially operating under steady state condition with load demand (P_{ref}) of 10 kW when wind speed was 9 m/sec. At 0.5 sec P_{ref} was suddenly changed from 10 kW to 35 kW. As stated earlier, for wind speed of 9 m/sec, P_{max} is 29 kW. Thus the purpose of this simulation case is to demonstrate ability of the controller to move from power sufficient mode to power insufficient mode dynamically. Figure 6 shows response of the system to sudden increase in load demand and its effect on P_{load}, V_{dc}, w and Currents. As can be seen the controller successfully switches from power sufficient mode to power insufficient mode and the system starts operating at MPP (Maximum Power Point). As the power demand is more than the P_{max}, the load network will draw remaining power from the grid.

Case 3: Sudden change in climatic conditions

WECS systems often encounter sudden climatic changes, which may sometimes lead to system instability. In this case simulations were carried out to study the effects of varying weather conditions by changing wind speed. The system is initially operating at P_{ref}=15 kW, with wind speed 9 m/sec. At t=0.5 sec the wind speed is changed from 9m/sec to 8 m/sec. As can be seen from Figure 7, the controller adjusts w_{ref} so as to maintain power balance at all times.

6. CONCLUSIONS

A power balancing control strategy for limited power point tracking is proposed for grid-connected WECSs. The main advantage of the proposed methodology is that back-up energy storage devices are not required for maintaining power balance and constant DC link voltage. Elimination of battery banks eliminates its maintenance and cost factor; this will improve overall economy of WECS economy. The proposed limited power point control algorithm can operate the controlled converter in two modes i.e. at maximum power point (power insufficient) and limited power point (power sufficient). The performance of the proposed control strategy demonstrated its effectiveness and applicability for grid-connected WECSs under varying load and weather conditions.

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