

MPPT Control Methods in Wind Energy Conversion Systems

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1. Introduction

Wind energy conversion systems have been attracting wide attention as a renewable energy source due to depleting fossil fuel reserves and environmental concerns as a direct consequence of using fossil fuel and nuclear energy sources. Wind energy, even though abundant, varies continually as wind speed changes throughout the day. The amount of power output from a wind energy conversion system (WECS) depends upon the accuracy with which the peak power points are tracked by the maximum power point tracking (MPPT) controller of the WECS control system irrespective of the type of generator used.

This study provides a review of past and present MPPT controllers used for extracting maximum power from the WECS using permanent magnet synchronous generators (PMSG), squirrel cage induction generators (SCIG) and doubly fed induction generator (DFIG). These controllers can be classified into three main control methods, namely tip speed ratio (TSR) control, power signal feedback (PSF) control and hill-climb search (HCS) control. The chapter starts with a brief background of wind energy conversion systems. Then, main MPPT control methods are presented, after which, MPPT controllers used for extracting maximum possible power in WECS are presented.

2. Wind energy background

Power produced by a wind turbine is given by [1]

$$P_m = 0.5\pi\rho C_p(\lambda, \beta)R^2 v_w^3 \quad (1)$$

where R is the turbine radius, v_w is the wind speed, ρ is the air density, C_p is the power coefficient, λ is the tip speed ratio and β is the pitch angle. In this work β is set to zero. The tip speed ratio is given by:

$$\lambda = \omega_r R / v_w \quad (2)$$

where ω_r is the turbine angular speed. The dynamic equation of the wind turbine is given as

$$d\omega_r / dt = (1 / J)[T_m - T_L - F\omega_r] \quad (3)$$

where J is the system inertia, F is the viscous friction coefficient, T_m is the torque developed by the turbine, T_L is the torque due to load which in this case is the generator torque. The target optimum power from a wind turbine can be written as

$$P_{\max} = K_{opt}\omega_{r_opt}^3 \quad (4)$$

where

$$K_{opt} = \frac{0.5\pi\rho C_{p\max}R^5}{\lambda_{opt}^3} \quad (5)$$

$$\omega_{opt} = \frac{\lambda_{opt}v_w}{R} \quad (6)$$

Fig.1 shows turbine mechanical power as a function of rotor speed at various wind speeds. The power for a certain wind speed is maximum at a certain value of rotor speed called optimum rotor speed ω_{opt} . This is the speed which corresponds to optimum tip speed ratio λ_{opt} . In order to have maximum possible power, the turbine should always operate at λ_{opt} . This is possible by controlling the rotational speed of the turbine so that it always rotates at the optimum speed of rotation.

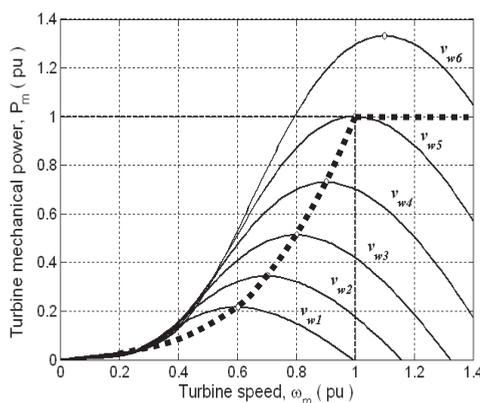


Fig. 1. Turbine mechanical power as a function of rotor speed for various wind speeds.

3. Maximum power point tracking control

Wind generation system has been attracting wide attention as a renewable energy source due to depleting fossil fuel reserves and environmental concerns as a direct consequence of using fossil fuel and nuclear energy sources. Wind energy, even though abundant, varies

continually as wind speed changes throughout the day. Amount of power output from a WECS depends upon the accuracy with which the peak power points are tracked by the MPPT controller of the WECS control system irrespective of the type of generator used. The maximum power extraction algorithms researched so far can be classified into three main control methods, namely tip speed ratio (TSR) control, power signal feedback (PSF) control and hill-climb search (HCS) control [2].

The TSR control method regulates the rotational speed of the generator in order to maintain the TSR to an optimum value at which power extracted is maximum. This method requires both the wind speed and the turbine speed to be measured or estimated in addition to requiring the knowledge of optimum TSR of the turbine in order for the system to be able extract maximum possible power. Fig. 2 shows the block diagram of a WECS with TSR control.

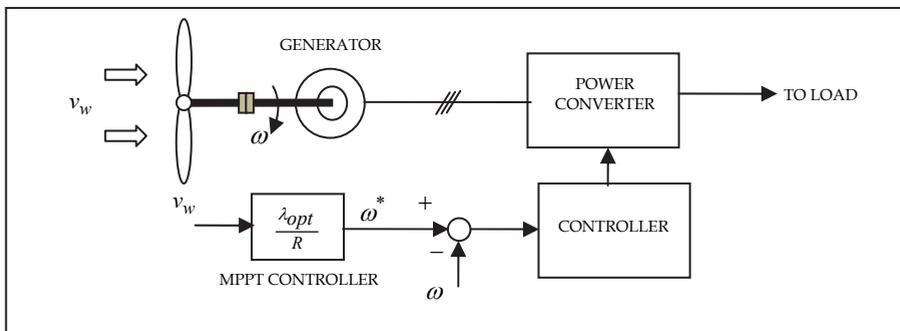


Fig. 2. Tip speed ratio control of WECS.

In PSF control, it is required to have the knowledge of the wind turbine's maximum power curve, and track this curve through its control mechanisms. The maximum power curves need to be obtained via simulations or off-line experiment on individual wind turbines. In this method, reference power is generated either using a recorded maximum power curve or using the mechanical power equation of the wind turbine where wind speed or the rotor speed is used as the input. Fig. 3 shows the block diagram of a WECS with PSF controller for maximum power extraction.

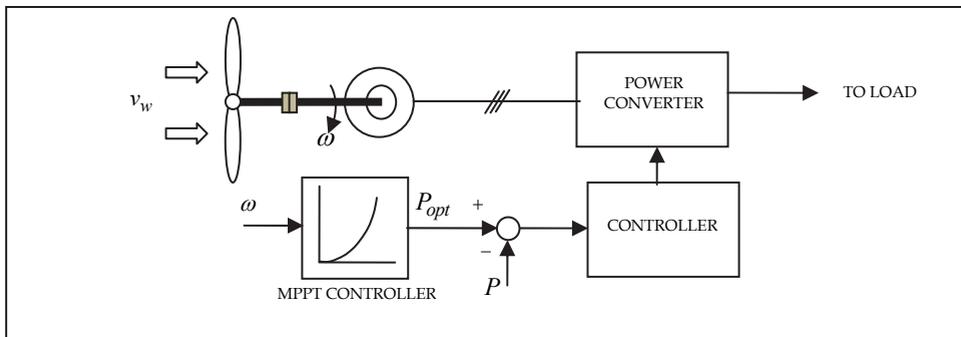


Fig. 3. Power signal feedback control.

The HCS control algorithm continuously searches for the peak power of the wind turbine. It can overcome some of the common problems normally associated with the other two methods. The tracking algorithm, depending upon the location of the operating point and relation between the changes in power and speed, computes the desired optimum signal in order to drive the system to the point of maximum power. Fig. 4 shows the principle of HCS control and Fig. 5 shows a WECS with HCS controller for tracking maximum power points.

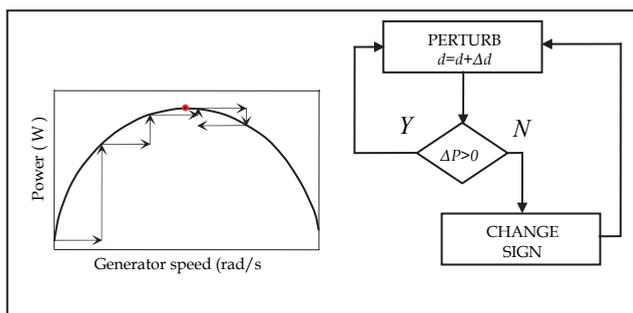


Fig. 4. HCS Control Principle.

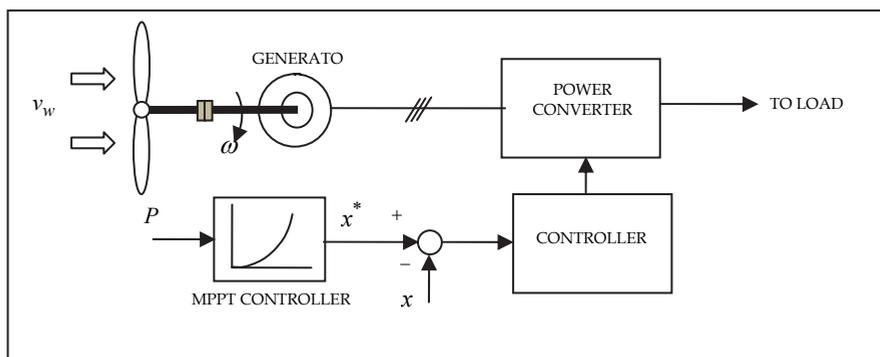


Fig. 5. WECS with hill climb search control.

4. MPPT control methods for PMSG based WECS

Permanent Magnet Synchronous Generator is favoured more and more in developing new designs because of higher efficiency, high power density, availability of high-energy permanent magnet material at reasonable price, and possibility of smaller turbine diameter in direct drive applications. Presently, a lot of research efforts are directed towards designing of WECS which is reliable, having low wear and tear, compact, efficient, having low noise and maintenance cost; such a WECS is realisable in the form of a direct drive PMSG wind energy conversion system.

There are three commonly used configurations for WECS with these machines for converting variable voltage and variable frequency power to a fixed frequency and fixed voltage power. The power electronics converter configurations most commonly used for PMSG WECS are shown in Fig. 6.

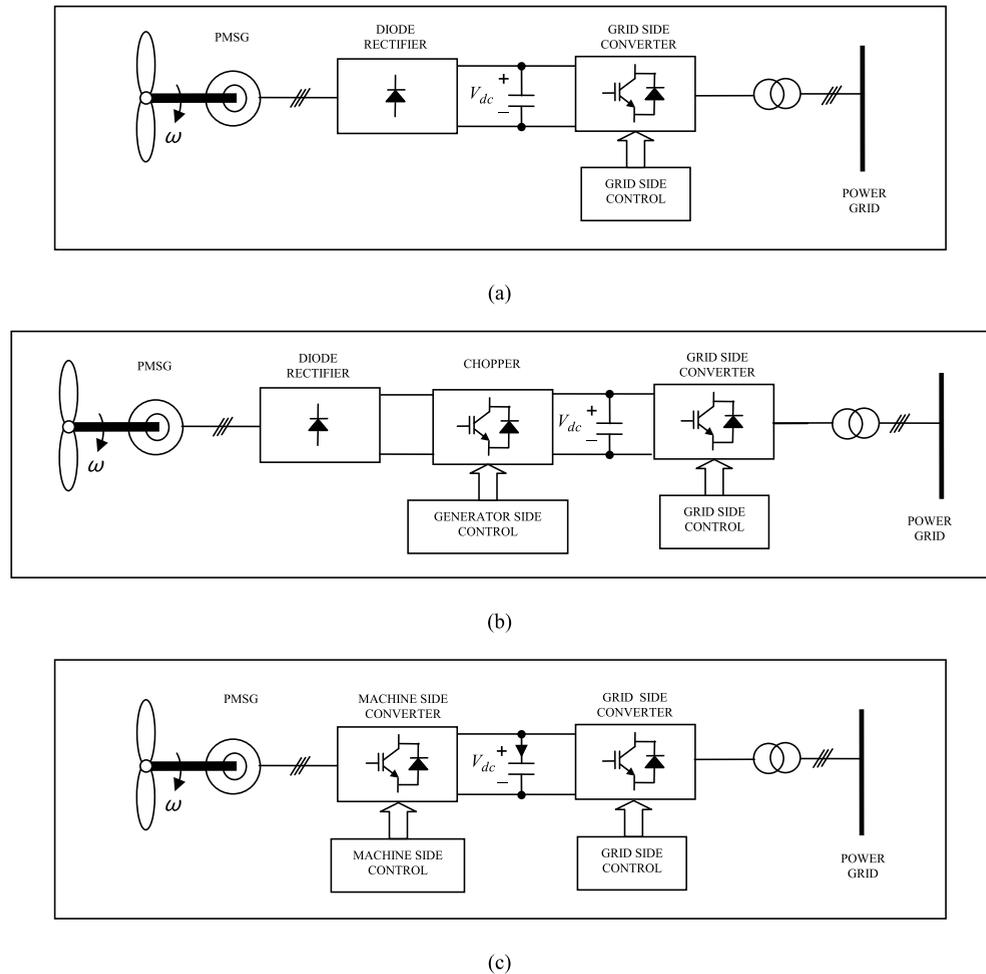


Fig. 6. PMSG wind energy conversion systems

Depending upon the power electronics converter configuration used with a particular PMSG WECS a suitable MPPT controller is developed for its control. All the three methods of MPPT control algorithm are found to be in use for the control of PMSG WECS.

4.1 Tip speed ratio control

A wind speed estimation based TSR control is proposed in [3] in order to track the peak power points. The wind speed is estimated using neural networks, and further, using the estimated wind speed and knowledge of optimal TSR, the optimal rotor speed command is computed. The generated optimal speed command is applied to the speed control loop of the WECS control system. The PI controller controls the actual rotor speed to the desired value by varying the switching ratio of the PWM inverter. The control target of the inverter is the output power delivered to the load. This WECS uses the power converter

configuration shown in Fig. 6 (a). The block diagram of the ANN-based MPPT controller module is shown in Fig. 7. The inputs to the ANN are the rotor speed ω_r and mechanical power P_m . The P_m is obtained using the relation

$$P_m = \omega_r \left(J \frac{d\omega_r}{dt} \right) + P_e \tag{7}$$

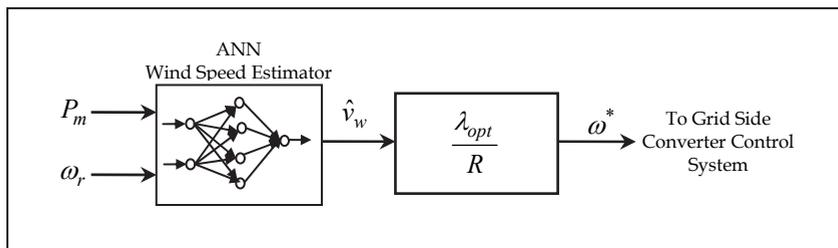


Fig. 7. ANN-based MPPT control module of turbine rotor speed.

4.2 Power signal feedback

In [4], the turbine power equation is used for obtaining reference power for PSF based MPPT control of PMSG WECS. Fig. 8 shows the block diagram for the PSF control signal generation. Using equation (8) we have:

$$P_{opt} = K_{opt} \omega_r^3 \tag{8}$$

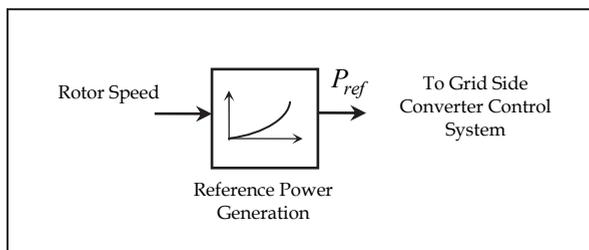


Fig. 8. Reference power generation for PSF control.

The PSF control block generates the reference power command P_{ref} using (8) which is then applied to the grid side converter control system for maximum power extraction.

4.3 Hill climb search control

In [2-17] Hill climb search method of MPPT control for PMSG WECS are proposed. The control algorithm proposed in [2] uses the principle of search-remember-reuse technique. The method uses memory for storing peak power points, obtained during training process, which are used later for tracking maximum power points. The principle behind this algorithm is a search-remember-reuse process. The algorithm will start from an empty intelligent memory with a relatively poor initial performance. During the execution, training

mode will use the searched data by advanced hill-climb search to gradually train the intelligent memory to record the training experience. The algorithm will reuse the recorded data in application mode for fast execution. This “search-remember-reuse” will repeat itself until an accurate memory of system characteristics is established. Therefore, after the algorithm is adequately trained, its power extraction performance is optimized. Since the intelligent memory is trained on-line during system operation, such a process is also referred as on-line training process. The structure of the advanced hill-climb search control algorithm is shown in Fig. 9. Every execution cycle starts with sampling of V_{dc} and P_0 , and calculation of their differentials. The mode switch rule directs the control into one of three execution modes, namely initial mode, training mode, and application mode. The inverter current demand I_{dm} is calculated in that mode and fed to the inverter to regulate the system power output. I_{dm} is defined as the requested peak value of the sinusoidal inverter output current. The maximum power error driven mechanism (MPED) provides the system with a preliminary optimized operating point when the intelligent memory is empty. The reference signal for MPED is the P_{max} which can only be reached when wind is sufficiently high. The intelligent memory records the system maximum power points and the corresponding control variables at different operating conditions. The direct current demand control (DCDC) utilizes the optimized relationship between the V_{dc} and I_{dm} recorded by the intelligent memory, and generates the command I_{dm} based on the present value of V_{dc} . For details about the method please refer to [2].

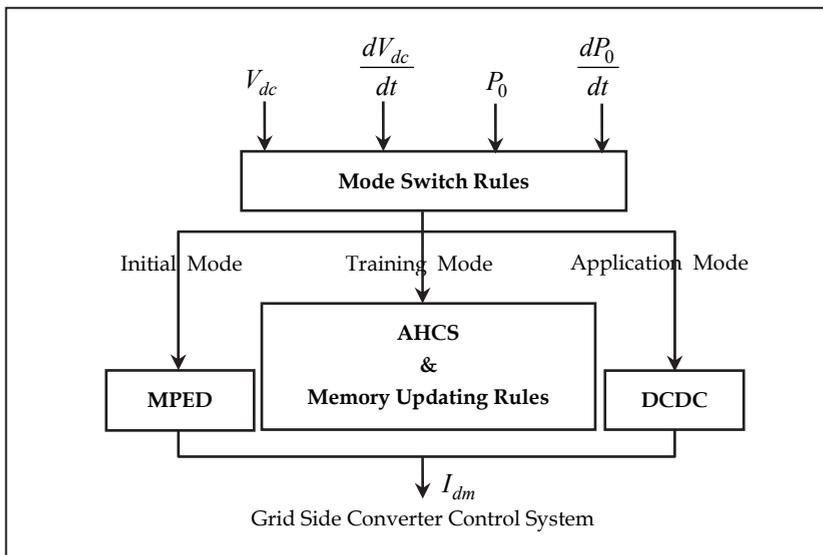


Fig. 9. Structure of advanced hill-climb search

The MPPT control proposed in [5] is based on directly adjusting the dc/dc converter duty cycle D according to the result of the comparison of successive wind generator (WG) output power measurements. Although the variation of wind speed with time is large, the power absorbed by the WG varies relatively slowly because of the slow dynamics of the turbine-

generator system. The problem of maximizing the WG output using the converter duty cycle as a control variable is effectively solved using the steepest ascent method given by

$$D_k = D_{k-1} + C_1 \cdot \frac{\Delta P_{k-1}}{\Delta D_{k-1}} \quad (9)$$

where D_k and D_{k-1} are the duty cycle values at k and $k-1$ sampling instant and C_1 is the step change.

The method is based on the fact that at maximum power point $dP/d\omega = 0$ and therefore $dP/dD = 0$ where D is the dc/dc converter duty cycle. This is possible because power as a function of duty cycle has a single extremum point coinciding with the maximum power point of WG, and the dc/dc converter duty-cycle adjustment according to the control law of (9) ensures convergence to the maximum power point under any wind-speed condition.

A HCS control method based on limit cycle is proposed in [6]. The MPPT control is performed via an integrator ramping up or down the current command signal of the grid side converter using the error in the dc link voltage regulated by a boost chopper. The reference current increases till the maximum power is obtained however, if it is increased further then the dc link voltage cannot be kept at constant because the power equilibrium cannot be maintained. Therefore, the dc link voltage begins to decrease and if it goes below a certain limit then, the integrator gain is changed to negative value decreasing the value of reference current. The MPPT control exhibits non linear oscillations about maximum power point called the limit cycle. In this method, the generated output power is automatically maximized by utilizing the inherent limit cycle phenomena of the system itself without requiring any information from the generator side, e.g. rotation speed, torque or instantaneous power etc.

In [7, 8] disturbance injection based HCS is proposed. The control algorithm proposes to inject a sinusoidal perturbation signal to the chopper. Then, the system output power is sampled at $\pi/2$ and $3\pi/2$ of each cycle, the difference of which decides about the next perturbation. The method does not require wind speed or rotor speed sensing.

In the HCS method proposed in [9], by controlling the output power as well as adjusting the electrical torque, the speed of the generator is indirectly controlled and then it obtains the optimum speed for driving the power to the maximum point. The maximum power error driven mechanism, operates like a traditional hill-climbing method, drives the output power gradually increasing to its maximum value by regulating the direction of current command according to the power variation trend. The maximum power differential speed control produces an additional step of current command based on the instantaneous difference of generator speeds, so that it can prevent the wind turbine from stalling at the suddenly dropping wind speed and achieve the object of maximum power extraction. It adds a faster control index into the control value which is proposed to be an exponential function of the differential generator speed and therefore it causes sharp increase or decrease in generator current command when wind speed increases or decreases suddenly. The controller generates current command for controlling the grid side converter. The method does not require wind speed measurement.

In [10] a variable tracking step is used to track the maximum power point. The constant step size used in conventional controllers is replaced with a scaled measure of the slope of power with respect to the perturbed generator speed $\Delta P/\Delta\omega$. The variable step uses a larger step size

when the operating point is far away from the peak due to the larger magnitude of $P-\omega$ slope and as the peak gets nearer, the step size should automatically approach to zero. The method uses torque current and speed to compute power. The speed step is computed as

$$\Delta\omega = k \cdot \frac{dP}{d\omega} \quad (10)$$

and the speed reference for the machine side converter control system is computed as

$$\omega^*(k+1) = \omega(k) + \Delta\omega(k) \quad (11)$$

In [11, 12] adaptive control algorithm for MPPT control is proposed. The control algorithm allows the generator to track the maximum power points of the wind turbine system under fluctuating wind conditions. The algorithm proposed initiates the TSR control with an approximate optimal TSR value. When the measured wind velocity is found to be stable, the algorithm switches to HCS to search for the true optimal point. When the true peak is reached, a memory table of the optimum generator speed versus the corresponding wind velocity is updated and then, the TSR is corrected. When the wind speed varies, the rotor speed reference is applied from the memory if a recorded data at current wind speed is present in the memory and if not, it is calculated using TSR. The MPPT control signal is given to the boost chopper for tracking the maximum power points. The method requires both wind speed and rotor speed measurement.

In [13] MPPT control of PMSG WECS is implemented via a dc-dc boost converter. The proposed MPPT strategy is based on directly adjusting the dc-dc converter duty cycle according to the result of the comparison of successive WTG output power measurements. The WECS MPPT algorithm operates by constantly perturbing the rectified output voltage V_{dc} of the WECS via the dc-dc boost converter duty cycle and comparing the actual output power with the previous perturbation sample. If the power is increasing, the perturbation will continue in the same direction in the following cycle so that the rotor speed will be increased, otherwise the perturbation direction will be inverted. When the optimal rotational speed of the rotor for a specific wind speed is reached, the HCS algorithm will have tracked the maximum power point and then will settle at or around this point. In [14] a buck-boost converter circuit is used to achieve the maximum power control of wind turbine driven PMSG WECS. The PMSG is suitably controlled according to the generator speed and thus the power from a wind turbine settles down on the maximum power point using the proposed MPPT control method. The method does not require the knowledge of wind turbine's maximum power curve or the information on wind velocity. It uses the dc link power as its input and the output is the chopper duty cycle.

The HCS MPPT control method in [15] uses power as the input and torque as the controller output. The optimum torque output of the controller is applied to the torque control loop of a DTC controlled PMSG. The controller does not require wind speed sensing.

The HCS MPPT control method presented in [16] combines the benefits of two of the commonly used MPPT methods: (i) the tracking method based on the optimum power versus speed characteristic and (ii) the HCS. The algorithm measures generator rotor speed and computes optimum torque T_{opt} , the torque which maximizes power. The actual torque T_t is also calculated. For a small error between the optimal and measured torque ΔT , the system performs a perturb and observe (P&O) process, based on the calculation of actual power, overlooking the use of the optimum $T-\omega$ characteristic. However, if the ΔT exceeds

a certain limit the duty cycle is commanded according to the optimum characteristic. In other words, the system tracks the maximum power point through a P&O process under normal circumstances; however, it uses the predefined $T - \omega$ characteristic in case the P&O algorithm is thrown off due to heavy disturbances such as sudden wind speed changes or improper initialization.

Neural networks based MPPT controller is presented in [17]. The method proposed uses Jordan recurrent multilayer ANN with one hidden layer. The weights of the networks are continuously modified by back propagation during the operation of the WECS with online training. The control system continuously searches ways to reach the peak power point. Optimum rotor speed, which is the output of the controller, is used as the reference speed for the vector controlled machine side converter control system.

5. MPPT control methods for SCIG based WECS

The use of induction generators (IG) is advantageous since they are relatively inexpensive, robust, and require low maintenance. The nature of IG is unlike that of PMSG; they need bi-directional power flow in the generator-side converter since they require external reactive power support from the grid. Modern IG WECS are equipped with PWM back-to-back frequency converter which also allows advanced control algorithms to be implemented. However, other converter configurations are possible and can be found in the literature. SCIG WECS with a back-to-back converter configuration is shown in Fig. 10. The MPPT control in such system is realized using the machine side control system. All the existing MPPT control algorithm scan be implemented for the control of IG WECS.

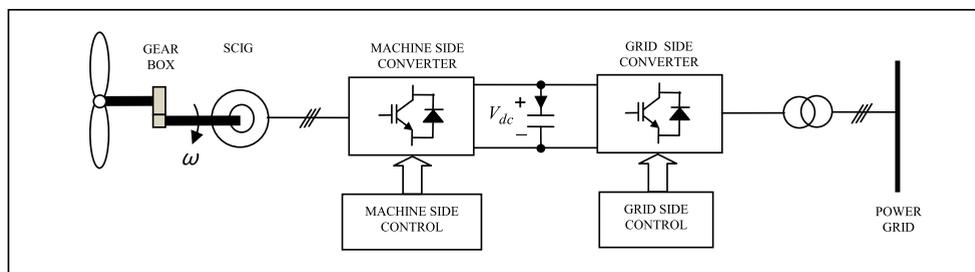


Fig. 10. SCIG WECS

5.1 Tip speed ratio control

In [13, 18, 19], TSR control method of MPPT control for SCIG WECS are presented. In the TSR control method presented in [18] the wind speed is measured for obtaining optimum rotor speed using the value of optimum tip speed ratio. The optimum TSR is obtained from the turbine's $C_p - \lambda$ curve. The rotor speed required for implementing speed feed-back control is estimated using a speed observer. The speed control is exercised using a fuzzy neural network controller.

Wind-speed estimation based MPPT control are proposed in [3, 19]. In [3], an ANN wind speed estimation based TSR control method was used for implementing MPPT control of SCIG WECS. Here, the optimum speed command was generated by the MPPT controller for speed control loop of machine side converter control system enabling the WECS to extract

optimum energy. The method has been presented in section (4.1). The wind speed estimation method in [19] is based on the theory of support-vector regression (SVR). The inputs to the wind-speed estimator are the wind-turbine power and rotational speed. A specified model, which relates the inputs to the output, is obtained by offline training. Then, the wind speed is determined online from the instantaneous inputs. The estimated wind speed is used for MPPT control of SCIG WECS.

5.2 Power signal feedback

In [20], fuzzy logic controller is used to track the maximum power point. The method uses wind speed as the input in order to generate reference power signal. Maximum power output P_{max} of the WECS at different wind velocity v_w is computed and the data obtained is used to relate P_{max} to v_w using polynomial curve fit as given by

$$P_{max} = -0.3 + 1.08v_w - 0.125v_w^2 + 0.842v_w^3 \quad (12)$$

The reference power at the rectifier output is computed using the maximum power given by (12) as

$$P_{ref} = \eta_G \eta_R P_{max} \quad (13)$$

The actual power output of the rectifier P_o is compared to the reference power P_{ref} and any mismatch is used by the fuzzy logic controller to change the modulation index M for the grid side converter control.

5.3 Hill climb search control

HCS control of SCIG WECS are presented in [21, 22]. In [21], a fuzzy logic based HCS controller for MPPT control is proposed. The block diagram of the fuzzy controller is shown in Fig. 11. In the proposed method, the controller, using P_o as input generates at its output the optimum rotor speed. Further, the controller uses rotor speed in order to reduce sensitivity to speed variation. The increments or decrements in output power due to an increment or decrement in speed is estimated. If change in power ΔP_o is positive with last positive change in speed $\Delta \omega_r$, indicated in Fig. 11 by $L\Delta \omega_r (pu)$, the search is continued in the same direction. If, on the other hand, $+\Delta \omega_r$ causes $-\Delta P_o$, the direction of search is reversed. The variables ΔP_o , $\Delta \omega_r$ and $L\Delta \omega_r$ are described by membership functions and rule table. In order to avoid getting trapped in local minima, the output $\Delta \omega_r$ is added to some amount of $L\Delta \omega_r$ in order to give some momentum and continue the search. The scale factors KPO and KWR are generated as a function of generator speed so that the control becomes somewhat insensitive to speed variation. For details please refer to [21].

In [22], a fuzzy logic control is applied to generate the generator reference speed, which tracks the maximum power point at varying wind speeds. The principle of the FLC is to perturb the generator reference speed and to estimate the corresponding change of output power P_o . If the output power increases with the last increment, the searching process continues in the same direction. On the other hand, if the speed increment reduces the output power, the direction of the searching is reversed. The block diagram of the proposed controller is shown in Fig. 12. The fuzzy logic controller is efficient to track the maximum power point, especially in case of frequently changing wind conditions. The controller tracks the maximum power point and extracts the maximum output power under varying wind

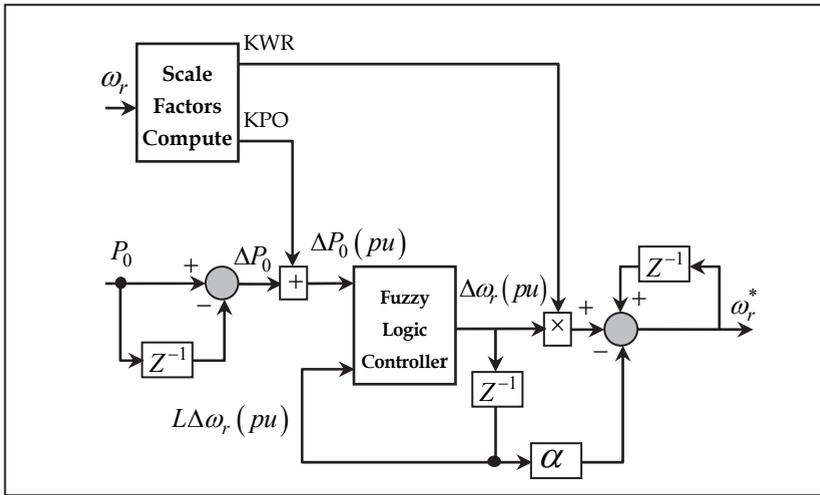


Fig. 11. Block diagram of fuzzy logic MPPT controller

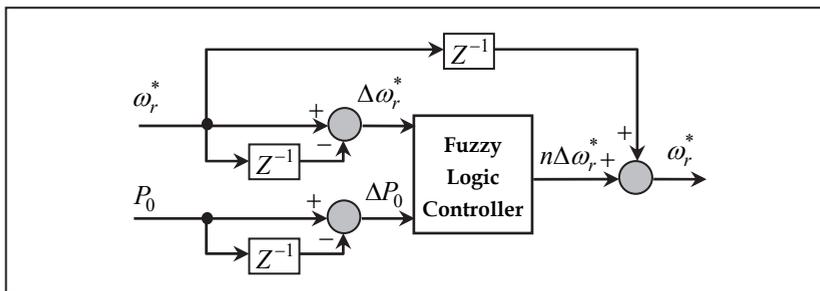


Fig. 12. Fuzzy MPPT controller

conditions. Two inputs $\Delta\omega_r^*$ and ΔP_0 are used as the control input signals and the output of the controller is the new speed reference speed which, after adding with previous speed command, forms the present reference speed. For more details, please refer to [22].

6. MPPT control methods for DFIG based WECS

The PMSG WECS and SCIG WECS have the disadvantages of having power converter rated at 1 p.u. of total system power making them more expensive. Inverter output filters and EMI filters are rated for 1 p.u. output power, making the filter design difficult and costly. Moreover, converter efficiency plays an important role in total system efficiency over the entire operating range. WECS with DFIG uses back to back converter configuration as is shown in Fig. 13. The power rating of such converter is lower than the machine total rating as the converter does not have to transfer the complete power developed by the DFIG. Such WECS has reduced inverter cost, as the inverter rating is typically 25% of total system power, while the speed range of variable speed WECS is 33% around the synchronous speed. It also has reduced cost of the inverter filters and EMI filters, because filters are rated

for 0.25 pu total system power, and inverter harmonics present a smaller fraction of total system harmonics. In this system power factor control can be implemented at lower cost, because the DFIG system basically operates similar to a synchronous generator. The converter has to provide only the excitation energy. The higher cost of the wound rotor induction machine over SCIG is compensated by the reduction in the sizing of the power converters and the increase in energy output. The DFIG is superior to the caged induction machine, due to its ability to produce above rated power. The MPPT control in such system is realized using the machine side control system.

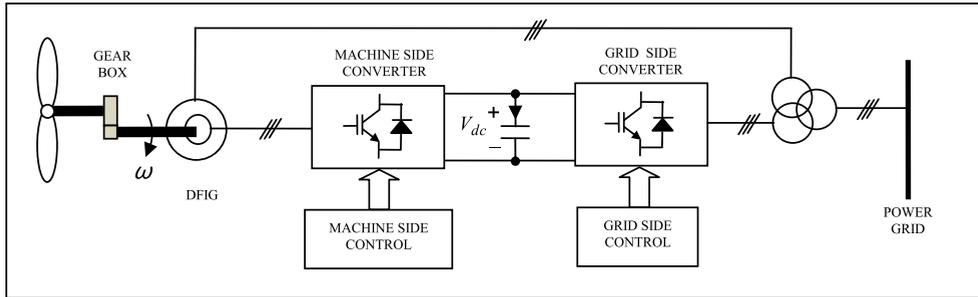


Fig. 13. DFIG WECS

6.1 Tip speed ratio control

TSR control is possible with wind speed measurement or estimation. In [23], a wind speed estimation based MPPT controller is proposed for controlling a brushless doubly fed induction generator WECS. The block diagram of the TSR controller is shown in Fig. 14. The optimum rotor speed ω_{opt} , which is the output of the controller, is used as the reference signal for the speed control loop of the machine side converter control system.

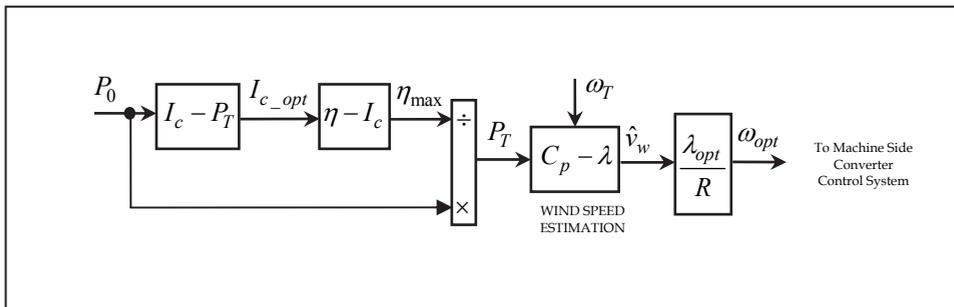


Fig. 14. Generation of optimum speed command

The method requires the total output power P_0 of the WECS and rotor speed as input to the MPPT controller. Using P_0 as the input to a look-up table of $I_c - P_0$ profile, optimum winding current I_{c_opt} is obtained. The maximum generator efficiency η_{max} is estimated at a particular control current optimized operating point using a stored efficiency versus optimum current characteristic of the generator. In the algorithm presented the relations I_c

versus P_T and I_c versus η were implemented using RBF neural networks. Then, generator input power P_T is calculated from the maximum efficiency η_{\max} and the measured output power P_0 . The next step involves wind speed estimation which is achieved using Newton-Raphson or bisection method. The estimated wind speed information is used to generate command optimum generator speed for optimum power extraction from WECS. For details of the proposed method please refer to [23]. The method is not new; similar work was earlier implemented for controlling a Brushless Doubly Fed Generator by Bhowmik et al [24]. In this method the Brushless Doubly Fed Generator was operated in synchronous mode and input to the controller was only the output power of the WECS.

6.2 Power signal feedback control

PSF control along with feedback linearization is used by [25] for tracking maximum power point. The input-output feedback linearization is done using active-reactive powers, $d-q$ rotor voltages, and active-reactive powers as the state, input and output vectors respectively. The references to the feedback linearization controller are the command active and reactive powers. The reference active power is obtained by subtracting the inertia power from the mechanical power which is obtained by multiplying speed with torque. A disturbance torque observer is designed in order to obtain the torque.

A fuzzy logic based PSF controller is presented in [26]. Here, a data driven design methodology capable of generating a Takagi-Sugeno-Kang (TSK) fuzzy model for maximum power extraction is proposed. The controller has two inputs and one output. The rotor speed and generator output power are the inputs, while the output is the estimated maximum power that can be generated. The TSK fuzzy system, by acquiring and processing the inputs at each sampling instant, calculates the maximum power that may be generated by the wind generator, as shown in Fig. 15.

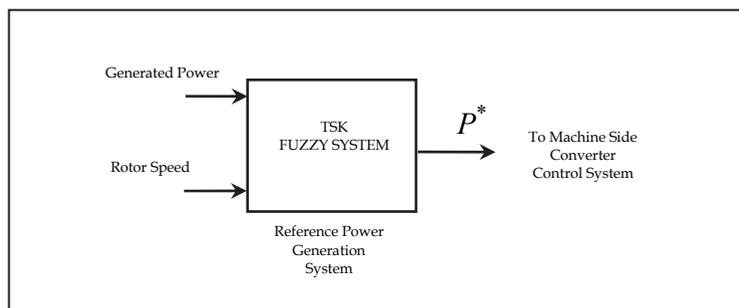


Fig. 15. TSK fuzzy MPPT controller

The approach is explained by considering the turbine power curves, as shown in Fig. 16. If the wind turbine initially operates at point A , the control system, using rotor speed and turbine power information, is able to derive the corresponding optimum operating point B , giving the desired rotor speed reference ω_B . The generator speed will therefore be controlled in order to reach the speed ω_B allowing the extraction of the maximum power P_B from the turbine.

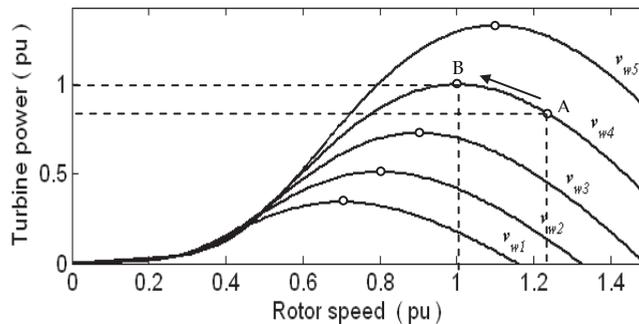


Fig. 16. Turbine power curves

6.3 Hill climb search control

HCS control method of MPPT control are presented in [27-29]. In [27], a simple HCS method is proposed wherein output power information required by the MPPT control algorithm is obtained using the dc link current and generator speed information. These two signals are the inputs to the MPPT controller whose output is the command speed signal required for maximum power extraction. The optimum speed command is applied to the speed control loop of the grid side converter control system. In this method, the signals proportional to the P_m is computed and compared with the previous value. When the result is positive, the process is repeated for a lower speed. The outcome of this next calculation then decides whether the generator speed is again to be increased or decreased by decrease or increase of the dc link current through setting the reference value of the current loop of the grid side converter control system. Once started, the controller continues to perturb itself by running through the loop, tracking to a new maximum once the operating point changes slightly. The output power increases until a maximum value is attained thus extracting maximum possible power.

The HCS control method presented in [28] operates the generator in speed control mode with the speed reference dynamically modified in accordance with the magnitude and direction of change of active power. Optimum power search algorithm proposed here uses the fact that $dP_o/d\omega=0$ at peak power point. The algorithm dynamically modifies the speed command in accordance with the magnitude and direction of change of active power in order to reach the peak power point.

In [29], the proposed MPPT method combines the ideas of sliding mode (SM) control and extremum seeking control (ESC). In this method only the active power of the generator is required as the input. The method does not require wind velocity measurement, wind-turbine parameters or rotor speed etc. The block diagram of the control system is shown in Fig. 17. In the figure ρ is the acceleration of P_{opt} . When the sign of derivative of ϵ changes, a sliding mode motion occurs and ω^* is steered towards the optimum value while P_o tracks P_{opt} . The speed reference for the vector control system is the optimal value resulting from the MPPT based on sliding mode ESC.

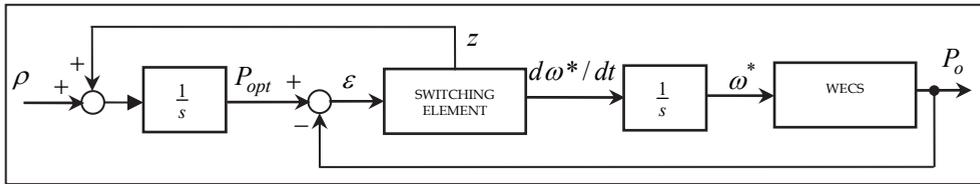


Fig. 17. Sliding mode extremum seeking MPPT control

7. Case study

An MPPT controller for variable speed WECS proposed in [30] is presented in this work as a case study. The method proposed in [30], does not require the knowledge of wind speed, air density or turbine parameters. The MPPT controller generates at its output the optimum speed command for speed control loop of rotor flux oriented vector controlled machine side converter control system using only the instantaneous active power as its input. The optimum speed commands, which enable the WECS to track peak power points, are generated in accordance with the variation of the active power output due to the change in the command speed generated by the controller. The proposed concept was analyzed in a direct drive variable speed PMSG WECS with back-to-back IGBT frequency converter. Vector control of the grid side converter was realized in the grid voltage vector reference frame. The complete WECS control system is shown in Fig. 18.

The MPPT controller computes the optimum speed for maximum power point using information on magnitude and direction of change in power output due to the change in command speed. The flow chart in Fig. 19 shows how the proposed MPPT controller is executed. The operation of the controller is explained below.

The active power $P_o(k)$ is measured, and if the difference between its values at present and previous sampling instants $\Delta P_o(k)$ is within a specified lower and upper power limits P_L and P_M respectively then, no action is taken; however, if the difference is outside this range, then certain necessary control action is taken. The control action taken depends upon the magnitude and direction of change in the active power due to the change in command speed.

- If the power in the present sampling instant is found to be increased i.e. $\Delta P_o(k) > 0$ either due to an increase in command speed or command speed remaining unchanged in the previous sampling instant i.e. $\Delta \omega^*(k-1) \geq 0$, then the command speed is incremented.
- If the power in present sampling instant is found to be increased i.e. $\Delta P_o(k) > 0$ due to reduction in command speed in the previous sampling instant i.e. $\Delta \omega^*(k-1) < 0$, then the command speed is decremented.
- Further, if the power in the present sampling instant is found to be decreased i.e. either due to a constant or increased command speed in the previous sampling instant i.e. $\Delta \omega^*(k-1) \geq 0$, then the command speed is decremented.
- Finally, if the power in the present sampling instant is found to be decreased i.e. $\Delta P_o(k) < 0$ due to a decrease in command speed in the previous sampling instant i.e. $\Delta \omega^*(k-1) < 0$, then the command speed is incremented.

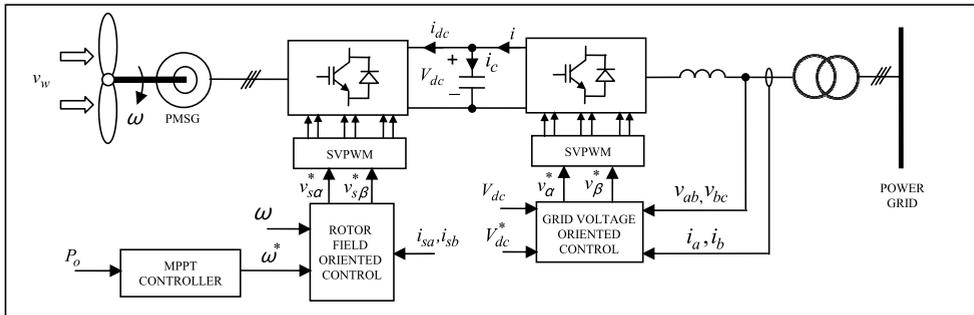


Fig. 18. PMSG wind energy conversion system.

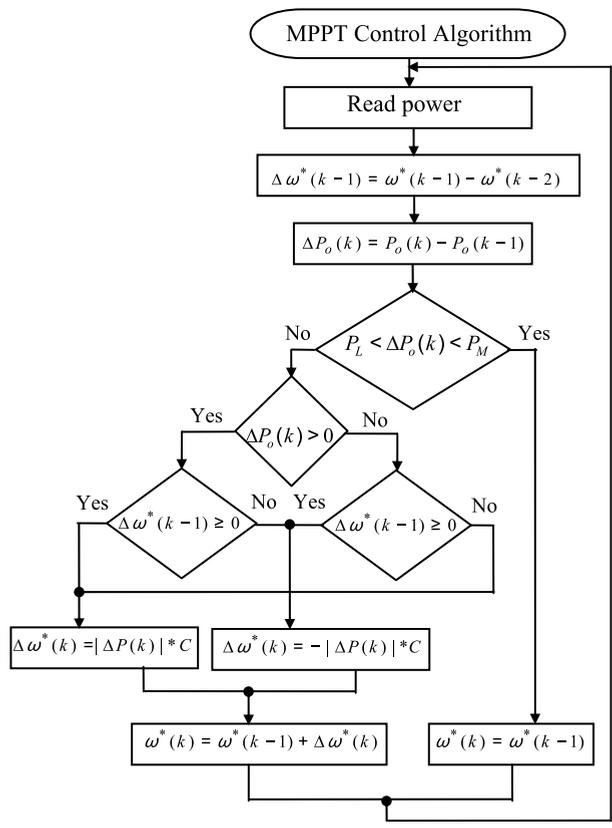


Fig. 19. Flow chart of MPPT controller.

The magnitude of change, if any, in the command speed in a control cycle is decided by the product of magnitude of power error $\Delta P_o(k)$ and C . The values C are decided by the speed of the wind. During the maximum power point tracking control process the product mentioned above decreases slowly and finally equals to zero at the peak power point.

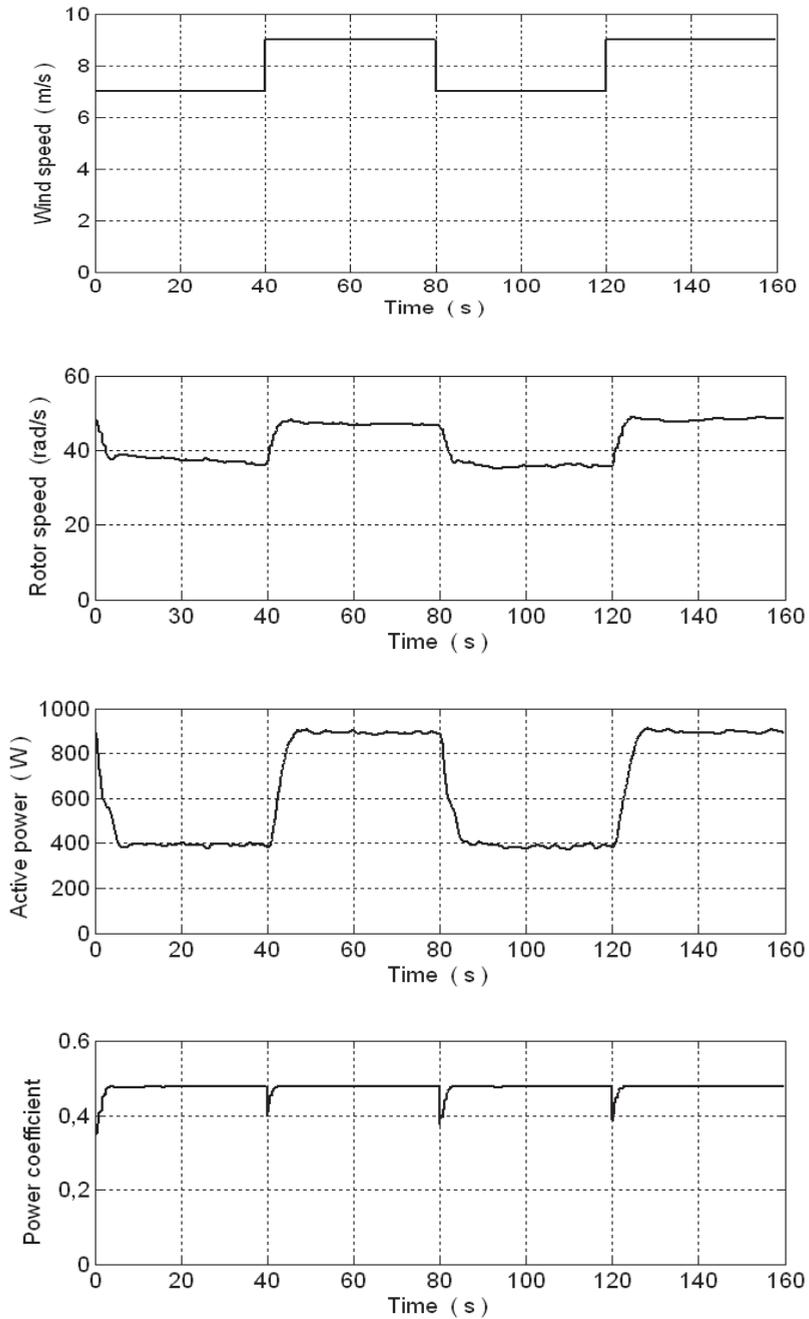


Fig. 20. Operation of the WECS under step wind speed profile.

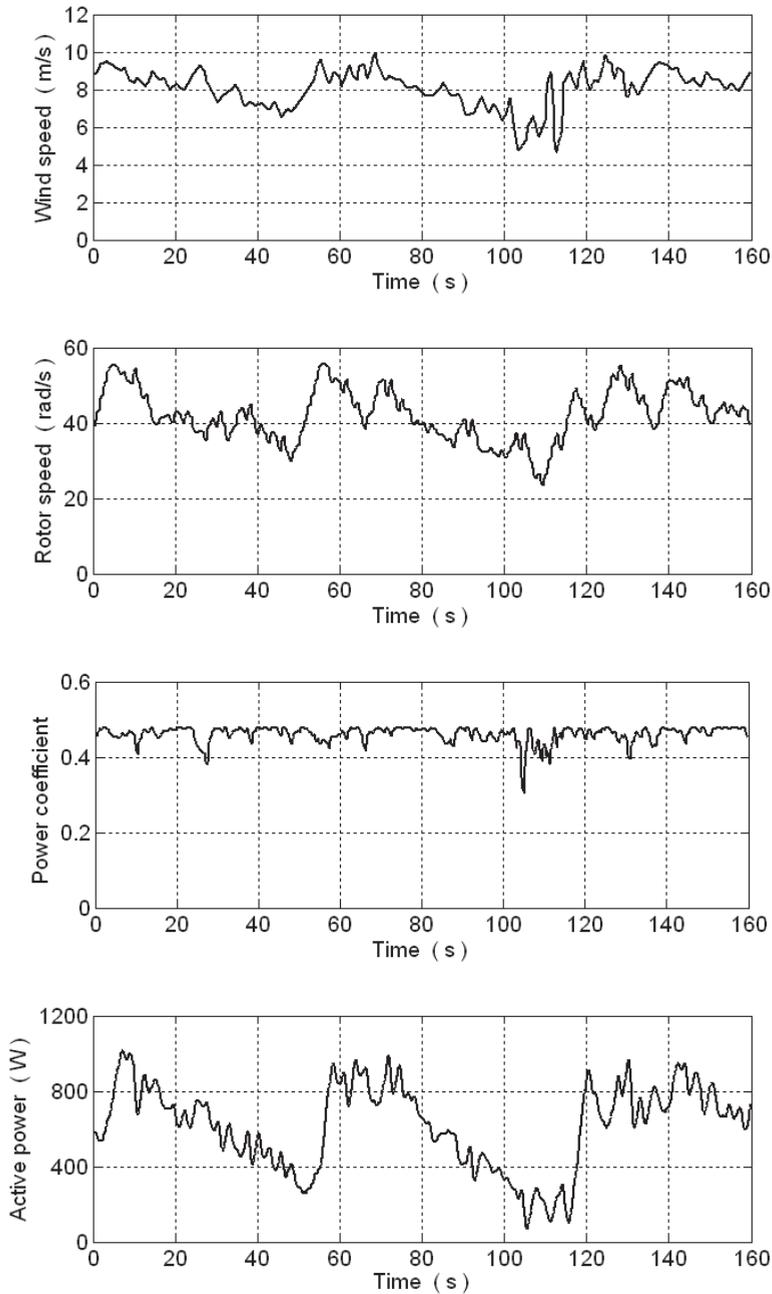


Fig. 21. Operation of the WECS under real wind speed profile.

In order to have good tracking capability at both high and low wind speeds, the value of C should change with the change in the speed of wind. The value of C should vary with variation in wind speed; however, as the wind speed is not measured, the value of command rotor speed is used to set its value. As the change in power with the variation in speed is lower at low speed, the value of C used at low speed is larger and its value decreases as speed increases. In this work, its values are determined by running several simulations with different values and choosing the ones which show best results.

The values of C , used in implementing the control algorithm, are computed by performing linear interpolation of 1.1 at 0 rad/s, 0.9 at 10 rad/s, 0.6 at 20 rad/s, 0.32 at 30 rad/s, 0.26 at 40 rad/s, 0.25 at 50 rad/s and 0.24 at 55 rad/s.

During the simulation, the d axis command current of the machine side converter control system is set to zero; whereas, for the grid side converter control system the q axis command current is set to zero. Simulation was carried out for two speed profiles applied to the WECS, incorporating the proposed MPPT controller.

Initially, a rectangular speed profile with a maximum of 9 m/s and a minimum of 7 m/s was applied to the PMSG WECS in order to see the performance of the proposed controller. The wind speed, rotor speed, power coefficient and active power output for this case are shown in Fig. 20. Good tracking capability was observed. Then, a real wind speed profile was applied to the PMSG wind generator system. Fig. 21 shows for this case, the wind speed, rotor speed, power coefficient and active power. The maximum value of C_p of the turbine considered was 0.48, and it was found that in worst case, the value of C_p was 0.33 which shows good performance of the proposed controller. It can therefore be concluded from the results of simulation that the proposed control algorithm has good capability of tracking peak power points. The method also has good application potential in other types of WECS.

8. Conclusions

Wind energy conversion system has been receiving widest attention among the various renewable energy systems. Extraction of maximum possible power from the available wind power has been an important research area among which wind speed sensorless MPPT control has been a very active area of research. In this chapter, a concise review of MPPT control methods proposed in various literatures for controlling WECS with various generators have been presented. There is a continuing effort to make converter and control schemes more efficient and cost effective in hopes of developing an economically viable solution to increasing environmental issues. Wind power generation has grown at an alarming rate in the past decade and will continue to do so as power electronic technology continues to advance.

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As the fastest growing source of energy in the world, wind has a very important role to play in the global energy mix. This text covers a spectrum of leading edge topics critical to the rapidly evolving wind power industry. The reader is introduced to the fundamentals of wind energy aerodynamics; then essential structural, mechanical, and electrical subjects are discussed. The book is composed of three sections that include the Aerodynamics and Environmental Loading of Wind Turbines, Structural and Electromechanical Elements of Wind Power Conversion, and Wind Turbine Control and System Integration. In addition to the fundamental rudiments illustrated, the reader will be exposed to specialized applied and advanced topics including magnetic suspension bearing systems, structural health monitoring, and the optimized integration of wind power into micro and smart grids.

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