Article

Coordinated Control Strategies for a Permanent Magnet Synchronous Generator Based Wind Energy Conversion System

Ramji Tiwari [1] [ID]**, Sanjeevikumar Padmanaban [2,*]** [ID] **and Ramesh Babu Neelakandan [1]** [ID]

[1] School of Electrical Engineering, VIT University, Vellore 632014, India; ramji.tiwari2015@vit.ac.in (R.T.); nrameshbabu@vit.ac.in (R.B.N.)

[2] Department of Electrical and Electronics Engineering, University of Johannesburg, Auckland Park 2006, South Africa

*   Correspondence: sanjeevi_12@yahoo.co.in; Tel.: +27-79-219-9845

Abstract: In this paper, a novel co-ordinated hybrid maximum power point tracking (MPPT)-pitch angle based on a radial basis function network (RBFN) is proposed for a variable speed variable pitch wind turbine. The proposed controller is used to maximise output power when the wind speed is low and optimise the power when the wind speed is high. The proposed controller provides robustness to the nonlinear characteristic of wind speed. It uses wind speed, generator speed, and generator power as input variables and utilises the duty cycle and the reference pitch angle as the output control variables. The duty cycle is used to control the converter so as to maximise the power output and the reference pitch angle is used to control the generator speed in order to control the generator output power in the above rated wind speed region. The effectiveness of the proposed controller was verified using MATLAB/Simulink software.

Keywords: wind energy conversion system; permanent magnet synchronous generator; maximum power point tracking; pitch angle; radial basis function network

1. Introduction

Renewable energy systems (RES) have drastically increased their contribution in the production of electrical energy, which is environmentally friendly, and thus minimising the dependency of the fossil fuel based power generation technique. Among the renewable based energy production systems, wind energy conversion systems (WECS) are mostly preferred for their wide availability and enhanced technology in implementation of the large capacity wind turbine. Due to steady growth in the increase of the power rating of wind turbines (WT) and integration to the power grid, additional advanced control strategies are required to make the wind energy systems more reliable and feasible for grid integration [1].

Currently, variable speed wind turbine (VSWT) systems are mostly preferred over fixed speed wind turbines (FSWT) because VSWT can harness the electrical power from all wind speed regions by controlling their shaft speed based on the wind velocity. Various variable speed turbines are commercially available on the market such as the doubly fed induction generator (DFIG) and the permanent magnet synchronous generator (PMSG). Among the VSWT, PMSG based WECS has received much attention because of its several advantages such as gear-less operation, high efficiency, low maintenance, less noise, and high robustness. Direct driven PMSG provides higher power output and lower mechanical stress [2]. The typical diagram of direct driven PMSG with basic topology and control strategies is shown in Figure 1.
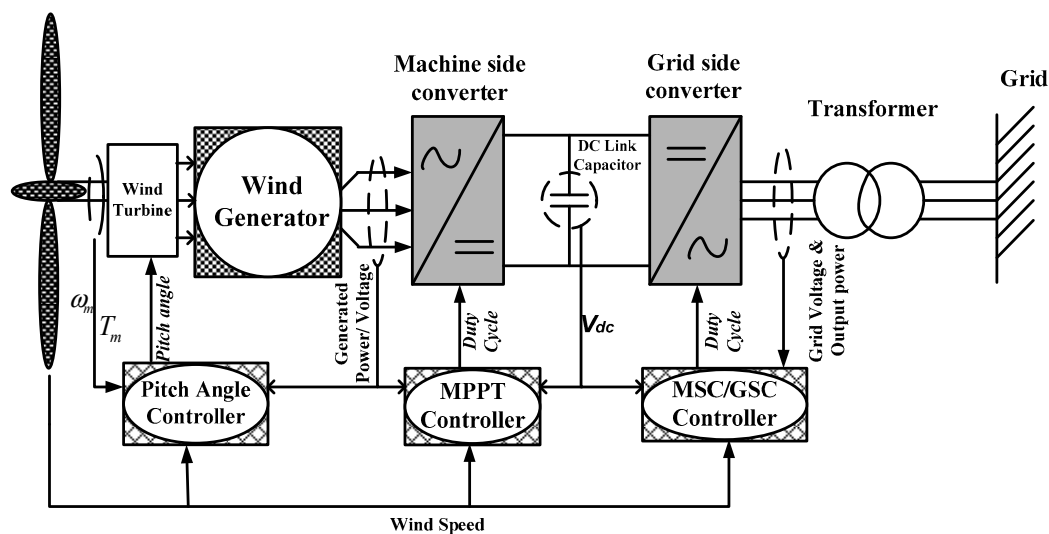
Figure 1. Basic topology of wind energy conversion systems (WECS) with control strategies.

The trend of installing large scale wind turbines will increase in the near future. Regardless of this, there are numerous challenges for the effective generation of wind power from the available wind speed as wind velocity is highly non-linear. Thus to optimise the WECS, various control strategies have been presented in the literature such as maximum power point tracking (MPPT), pitch angle and grid and machine side controller as shown in Figure 1 [1]. The machine and grid side controller are mainly used to penetrate the stabilised power in the grid following the grid code. The MPPT control strategy is employed to extract the maximum available power from the available wind whereas the pitch angle controller is used to regulate the power within the rated power when the power exceeds the rated power of the wind generator, which may lead to serious damage to the system [3]. The operating regions of MPPT and the pitch angle controller can be seen in Figure 2.
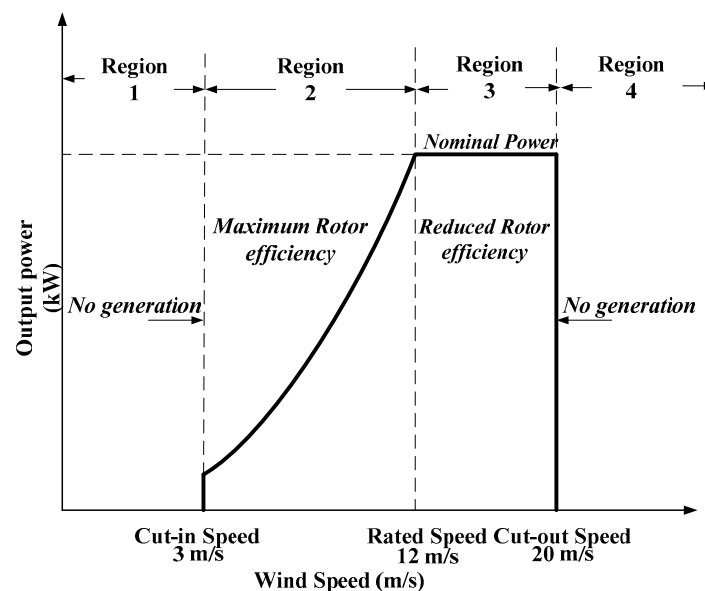

Figure 2. WECS operating regions based on wind speed.

The rapid variation and frequent discontinuity of wind pattern is one of the major operational problems which exist in WECS. The older wind turbines are equipped with basic control strategies

which are not suitable for the current scenario [4]. The repowering of an existing wind turbine with modern technology is the most preferred solution to upgrade wind farms. The new innovation in wind power technology should be installed in each wind turbine in order to achieve maximum efficiency and to be capable enough for grid integration [5]. The repowering of a wind turbine with the new technology is very costly which is an additional burden to the country or power producers.

In this paper, a novel hybrid MPPT and pitch angle control strategy is employed which can be equipped with the existing wind energy conversion system. The older wind turbines are usually of low rating. Thus they are usually not operated when the wind speed exceeds the rated wind speed. Thus to prevent this, pitch angle control strategy is employed. Pitch angle control strategy regulates the power when the wind velocity exceeds the rated speed and hence WECS is operated in that region. The MPPT strategy is used to increase the power yield when the wind velocity is below the rated wind speed. The MPPT control technique extracts the maximum available power which is present in the available wind speed. Thus by employing this intelligent hybrid control, the performance of WECS is improved as the system becomes robust and further the cost of repowering an existing wind turbine is also eliminated. This controller works on all the operating regions of the wind system.

2. Modelling of the Wind Energy Conversion System

The configuration of the proposed WECS is shown in Figure 3. The system consists of a direct driven PMSG, diode rectifier, boost converter and a proposed hybrid control strategy for a standalone system. The boost converter is incorporated with the MPPT control strategy which generates duty cycle according to the available wind speed [6]. The pitch angle is initiated when the wind velocity exceeds the rated wind speed. The pitch angle command controls the angle of the blade in such a way that the rotational speed of the shaft is kept at the optimum value.
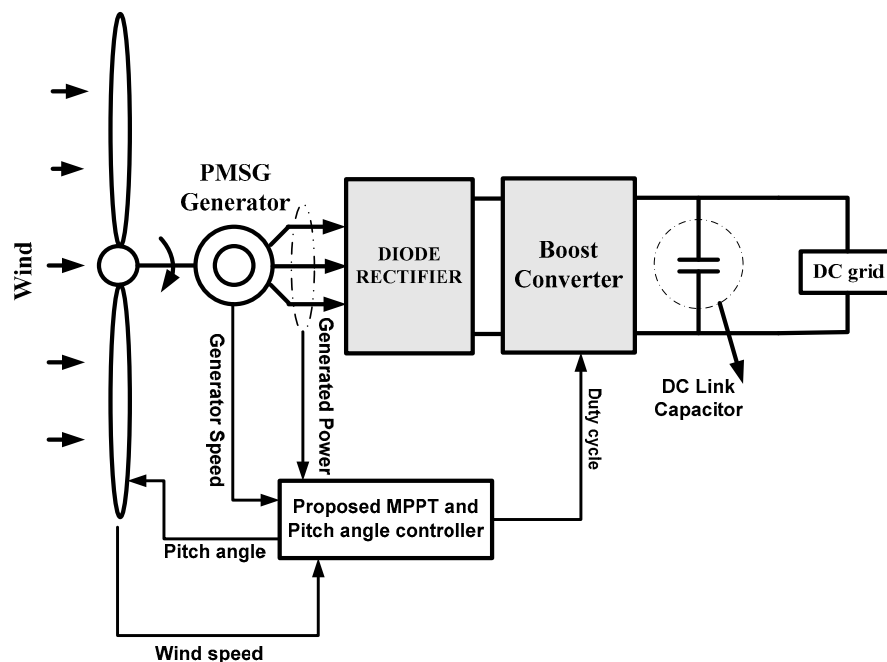

Figure 3. Proposed configuration for the permanent magnet synchronous generator (PMSG) based wind energy conversion system.

2.1. Wind Turbine Aerodynamic Model

The mechanical power (P_m) that can be extracted from the available wind by the wind turbine is given by [7],

$$P_m = \frac{1}{2}\rho A C_p(\lambda, \beta)v^3 \tag{1}$$

where ρ is the air density, A is the total area swept by the blades, v is the wind velocity and the power coefficient (C_p) of the wind system is determined using the tip speed ratio (λ) and the blade pitch angle (β). The pitch angle is always kept constant when the MPPT control strategy is operational. The optimal value at which the wind turbine extracts the maximum power (P_{max}) for the available wind speed is given by [8],

$$\lambda = \frac{\omega_r R}{v} \tag{2}$$

$$P_{max} = \frac{1}{2}\rho A \frac{C_{pmax} R^3}{\lambda_{opt}^3} * \omega_r^3 \tag{3}$$

where ω_r is the rotor rotational speed, R is the rotor radius and C_{pmax} is the maximum power coefficient at the optimal tip speed ratio (λ_{opt}). Figure 3 represents that the power generated (P_m) by the turbine purely depends upon the power coefficient (C_p) at a particular wind speed. The tendency of the wind turbine to extract the maximum power from the available wind speed declines by 9% after a life span of five years of operation [8]. Thus an efficient and intelligent control strategy should able to cope with the deficiency and extract the maximum power for an entire operational period.

2.2. PMSG Modelling

PMSG based WECS is the mostly preferred wind turbine for its flexibility and efficiency. The PMSG can deliver power at the desired power factor based on the requirement [9]. The dynamic equations of the three-phase salient pole PMSG in the *d–q* reference frame are described as [10],

$$\left. \begin{array}{l} v_q = Ri_q + p\lambda_q + \omega_s\lambda_d \\ v_d = Ri_d + p\lambda_d - \omega_s\lambda_q \end{array} \right\} \tag{4}$$

where v_d, i_d represents the stator voltage and current in the d axis and v_q, i_q in the q axis respectively. R denotes the stator resistance of PMSG. λ_q, λ_d are the stator flux linkages of the d, q axis respectively given as,

$$\left. \begin{array}{l} \lambda_q = L_q i_q \\ \lambda_d = L_d i_d + L_{md}I_{fd} \end{array} \right\} \tag{5}$$

where L_{md}, I_{fd} are the mutual inductance and magnetising current in the d axis. L_d, L_q are the self inductances of the d axis and q axis respectively. ω_s is the stator frequency, which is represented as,

$$\omega_s = n_p\omega_r \tag{6}$$

where n_p is the number of poles and ω_r is the rotation rotor speed.

3. Control Strategy of WECS

Wind energy conversion systems demonstrate the challenges of rapid variation in wind speed, nonlinearity and uncertainty. Thus an advanced controller is required to solve them efficiently. Integrating an advanced controller into WECS is done in order to increase efficiency in terms of power conversion and blade control design. Many researches have been carried out to develop a control strategy of WECS which can be integrated into the grid. The controllers must be simple, reliable, and cost effective. Moreover, they must able to withstand the fluctuations caused during their operation.

The most preferred control strategy for producing optimal and quality power from WECS are the MPPT and pitch angle controller [1].

3.1. Maximum Point Tracking Controller

To improve the energy capture efficiency in a modern WECS, an efficient and advanced MPPT technique is required. To operate the WECS at that specific point, various MPPT algorithms have been proposed in the literature [9,11–13]. The foremost controllers which are widely used are power signal feedback (PSF), hill climb search (HCS) or perturb and observe (P&O), tip speed ratio (TSR), optimal torque control (OTC), and soft-computing based techniques like fuzzy logic control (FLC) and artificial neural network (ANN) [1].

The power signal feedback (PSF) based MPPT controller technique tends to reduce the error between actual power and reference power. The PSF controller requires pre knowledge of the wind turbine. The value is recorded in a lookup table and the optimal power is obtained based on the available wind speed. The most advanced PSF controller uses DC voltage and DC current as an input rather than a power and speed shaft which reduces the use of a speed sensor. The major drawback of this system is the complexity in implementation. The HCS or P&O method is the widely preferred MPPT algorithm for its simplicity and low cost. This method is based on comparing the obtained power from the previous power and generating the appropriate duty cycle based on the comparison. The major drawback of this methodology in tracking the maximum power in the wind energy system is that it fails to follow the rapid variation in wind velocity. The convergence speed and efficiency is reduced when the P&O algorithm is subjected to the highly non-linear system. OTC control strategy adjusts the generated torque of the wind turbine based on the reference torque where the maximum power can be extracted at the particular wind speed. The reference torque is compared with the actual torque and an error signal is generated which is fed into the controller to maintain the optimal torque of the generator. OTC control strategy is simple, fast and efficient but the major drawback in this control strategy is that it does not measure the wind speed directly and hence the change in wind speed is not observed in the reference directly.

Thus to overcome the above issues, a soft computing based MPPT strategy like FLC and ANN controllers is implemented. Soft computing controllers do not require the mathematical knowledge of the system. Soft computing control strategy has a faster convergence speed and is highly reliable. Fuzzy logic based MPPT controller is suitable for a region where there is rapid and continuous variation in wind velocity. FLC technique has a fast response towards a change in system dynamics without the knowledge of system parameters. The FLC can overcome the high non-linearity of the system which is an important parameter for wind power system. The efficiency of FLC is based purely based on the selection of the input parameters and rule implementation. Thus an error caused by the control designer can have a severe effect on the efficiency. The major setback of FLC is the flexibility towards the changing of system parameters after implementation. To overcome this issue an ANN based controller is used. The ANN controllers use reference values to determine the maximum power of the system. The ANN method has a faster convergence speed than that of previous MPPT controllers. To realise an MPPT operation a power electronic converter (PEC) is necessary. In this paper, the boost converter is used as the PEC to interface the wind generator with the load.

3.2. Pitch Angle Controller

The pitch angle controller is implemented to limit the aerodynamic power captured by the wind turbine when the wind velocity is above the rated value [14]. Several pitch angle controllers have been suggested in past literature [1,15–18]. The most common pitch angle controllers are the proportional-integral (PI) controllers. They are simple and cost effective. However, the major disadvantage of the system in the performance of the controller is minimised due to frequent changing of the operating point because of the rapid variation in the wind speed. Another method to vary blade angle is the H-infinity. This controller gives enhanced performance of output power and provides

robustness to the variation of the wind. However, the major problem is that it is a complex system to design and when a constraint changes, the redesigning process is time consuming and difficult. Linear quadratic Gaussian (LQG) based pitch angle controller is robust in nature towards wind turbine parameter but it lacks in adaptation to the non-linearity of the wind system. The other technique which is employed in controlling the speed of the shaft is the sliding mode control. It is suitable for a highly non-linear system. The major disadvantage of the system is the requirement of a mathematical model of the system as well as sudden large changes in the wind turbine which increase the mechanical stress of the WECS thus damaging the mechanical parts associated with it.

To vary the pitch angle of the blade a more feasible and accurate soft computing technique is implemented. The fuzzy logic controller and artificial neural network are some of the soft computing based control strategies which are implemented to control the blade angle. These methods are reliable and robust with regard to the non-linear characteristics of pitch angle with wind speed. These controllers require wind speed information which uses an anemometer thus the cost of the overall system is increased. The reliance of the system on the sensor degrades the performance of the overall efficiency. In addition, installation of the anemometer is not feasible for old wind turbines when repowering is considered a primary agenda.

3.3. Proposed Coordinated Hybrid MPPT-Pitch Angle Control Strategy

The operating regions of the wind turbine are generally classified into two regions based on the wind speed as shown in Figure 2. In the region where the wind speed is lower than that of the rated wind speed, the turbine speed is controlled at the optimal value using MPPT strategy so that the maximum power can be extracted from the wind system based on the available wind speed (Region 2). In the region where the wind speed exceeds the rated value, the pitch angle control strategy optimises the output power by controlling the blade angle which limits the turbine speed (Region 3). The block diagram of the proposed control strategy using the radial basis function network (RBFN) is shown in Figure 4. The proposed topology consists of the boost converter and PMSG generator. The DC link capacitor (C_L) and output capacitor (C_O) are also present in the topology. The inputs for the RBFN control techniques are wind speed, generated speed, and generated power. The outputs of the proposed control are the duty cycle which is activated in the low wind speed region and the pitch angle which is triggered in the high wind speed region. In a region where the wind speed is below the rated wind velocity, the reference power (P_{ref}) is determined using Equation (3),

$$P_{ref} = K_{opt} * \omega_r^3 \tag{7}$$

where

$$K_{opt} = \frac{1}{2}\rho A \frac{C_{pmax} R^3}{\lambda_{opt}^3} \tag{8}$$

The pitch angle during Region 2 is kept near zero so as to increase the power co-efficient (C_p).

In the high wind speed region, the reference power (P_{ref}) is considered the same as the rated power of the wind turbine. The pitch angle should increase so as to decrease the power coefficient (C_p) thus limiting the power to the nominal value. In Region 3, the output power is maintained constant at the rated power of the wind turbine. Equation (3) is used to determine the relation between the power coefficient (C_p) and the pitch angle which is deduced in Equation (9)

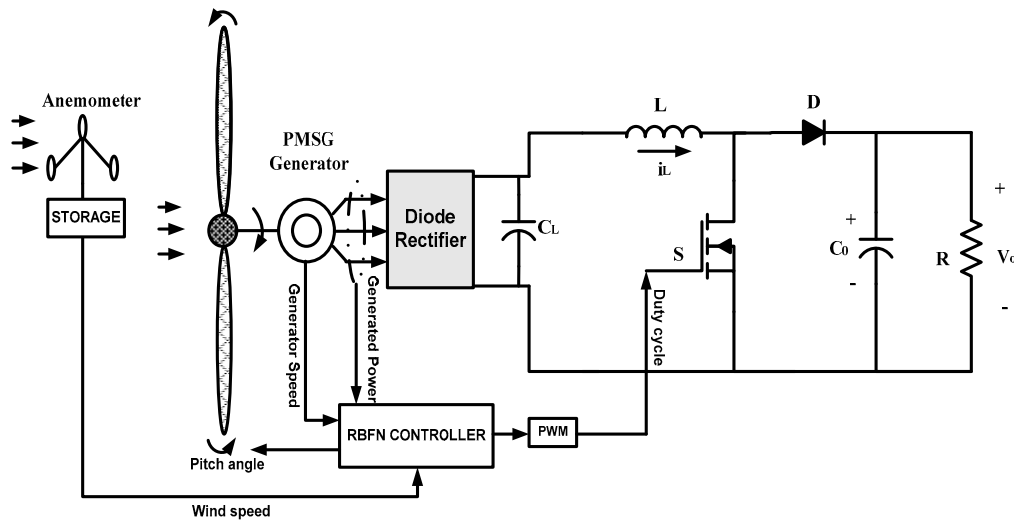$$C_p(\lambda, \beta) = \frac{2P_{max}}{\rho A v^3} \tag{9}$$

Figure 4. Proposed coordinated maximum power point tracking (MPPT) control strategy.

By replacing the nominal value of power, the optimal value of the power coefficient $C_{p\,opt}$ which maintains the power at the nominal (P_{nom}) value for variable wind speed is obtained from Equation (10).

$$C_p(\lambda, \beta) = C_{p\,opt}(\lambda, \beta) = \frac{2P_{nom}}{\rho A v^3} \tag{10}$$

Thus by optimising the power coefficient value and obtaining the new $C_p(\lambda, \beta)$ value the corresponding value of the pitch angle can be obtained using Equation (11),

$$C_p(\lambda, \beta) = (0.5 - 0.0167(\beta - 2)) \sin\left[\frac{\pi(\lambda + 0.1)}{18 - 0.3(\beta - 2)}\right] - 0.00184(\lambda - 3)(\beta - 2) \tag{11}$$

From Equation (11), the corresponding pitch angle value is obtained and fed to the system when the wind speed is higher than that of the rated wind speed.

Thus by utilising the Coordinated hybrid MPPT-Pitch angle control strategy, the output power can be maximised in the low wind speed region and optimised in the high wind speed region. Thus improving the overall efficiency of WECS and eliminating the need for repowering.

The WECS is highly non-linear in nature, thus an efficient and complex problem solving controller is required to enhance the overall performance. In this paper, RBFN based ANN control strategy was used to predict the precise duty cycle for the MPPT controller when the wind speed was below the rated speed as well as the specific angle for the blade for the pitch angle control strategy when the wind velocity exceeded the rated value.

Radial Basis Function Network

RBFN is a type of feed forward neural network which uses radial basis network as an activation function. The radial basis network is determined by the distance between the input and the prototype vector [19]. The RBFN is similar to the multi-layer perceptron (MLP) network. RBFN has three layers of input layer, hidden layer, and output layer as shown in Figure 5. The network neurons are connected to each other. From Figure 5, it can be seen that there is no weight coefficient between the input layer and the hidden layer. Hence the neuron in the hidden layer receives the same variables as in input layer. The training process of the RBFN network is carried out in two stages [20]. In the first stage, the unsupervised method is implemented where the parameter is governed by the radial basis function. In the second stage, the supervised training method is employed to train the weights which are the same as the back propagation algorithm [21].
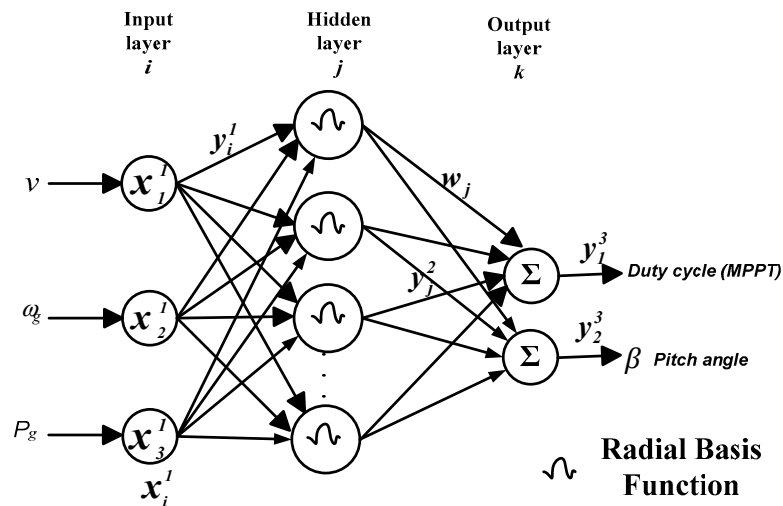
Figure 5. Proposed architecture of radial basis function network (RBFN) based hybrid control strategy.

In this paper, the RBFN controller is implemented to control the WECS based on the wind speed regions. In Region 2 where the wind speed is lower than that of the rated wind speed, the RBFN network generates the duty cycle for the PEC based on the corresponding wind speed to maximise the output power of the system. In Region 3 where the wind speed is greater than that of the rated wind velocity, the RBFN gives the appropriate pitch angle to the blades of the wind turbine to limit the output power. The wind speed, generated output power, and generator speed are fed to the input neurons of the RBFN which are used to compute the duty cycle and pitch angle as the output neuron based on the wind speed. The key considerations of the selection of input variables are the relevant data, training network, computational effort, dimensionality, and comprehensibility. The important parameters which are suggested for input selection in the neural network are the availability of the variables, correlation between the selected input variables, and inputs with minimum or zero prediction [22].

The basic nodes of operation are characterized into three layers [23],

The inputs of the three neurons in this layer are transmitted directly to the next layer. The net input and output are represented as,

$$\left.\begin{array}{l} net_i^1 = x_i^1(N) \\ y_i^1(N) = f_i^1\left(net_i^1(N)\right) = net_i^1(N) \end{array}\right\}_{i=1,2,3} \tag{12}$$

where x_i^1 is the input layer which consists of x_1^1 as the wind speed, x_2^1 as the generator power, and x_3^1 as the generator speed. The net_i^1 represents the net sum of nodes of the input layer and y_i^1 is the output of the input layer which is fetched to the hidden layer with respect to the node i.

The neurons in the hidden layer perform using the Gaussian membership function in RBFN. The net input and output of the hidden layer are represented as,

$$\left.\begin{array}{l} net_j^2(N) = -\left(X - M_j\right)^T \sum_j \left(X - M_j\right) \\ y_j^2(N) = f_j^2\left(net_j^2(N)\right) = \exp\left(net_j^2(N)\right) \end{array}\right\}_{j=1,2,\dots,800} \tag{13}$$

where $M_j = \left[m_{1j}, m_{2j}, \dots, m_{ij}\right]^T$ is the mean of the Gaussian function and the standard deviation of the Gaussian function is denoted as $\sum_j = diag\left[1/\sigma_{1j}^2, 1/\sigma_{2j}^2, \dots, 1/\sigma_{ij}^2\right]^T$.

The output layer computes two neurons which are determined by node k. The MPPT control signal and pitch angle control signal are generated in this layer by summing all the incoming signals with the linear activation function. The node k-1 represents the duty cycle based on the wind speed and node k-2 represents the pitch angle.

$$\left.\begin{array}{l} net_k^3 = \sum_j w_j y_j^2(N) \\ y_k^3(N) = f_{ki}^3\big(net_k^3(N)\big) = net_k^3(N)_{k=1,2} \end{array}\right\} \tag{14}$$

where w_j is the weight which connects the hidden layer and output layer.

Supervised learning is implemented once the RBFN is initialised to train the system. The training method is the same as the back propagation algorithm which is used to adjust the RBFN parameters using the training patterns. The error of each layer is calculated and updated by the supervised learning algorithm in order to track the performance of the wind system and act appropriately. The error of each output neuron is calculated using the squared error function. The total error of the system is given as [24,25]

$$E_{total} = \sum \frac{1}{2}(target - output)^2 \tag{15}$$

where the target refers to the pre-defined data and the output is the data obtained.

To evaluate the effectiveness of the proposed controller, the RBFN based controller is utilised for the system when only the MPPT controller and pitch angle control strategy are employed as shown in Figures 6 and 7. The wind speed and generated power are taken as the input parameters of the controller technique whereas the duty cycle is generated as the output of the power electronic converter (PEC) when only MPPT control strategy is used. The RBFN based MPPT control strategy implemented in this topology is shown in Figure 6 [25].

The wind speed and generated speed are considered as the input for the pitch angle control strategy. The ripple components of the generator speed and the output power are also eliminated and the parameters are subjected within the rated value. Figure 7 shows the pitch angle control strategy [26–33].
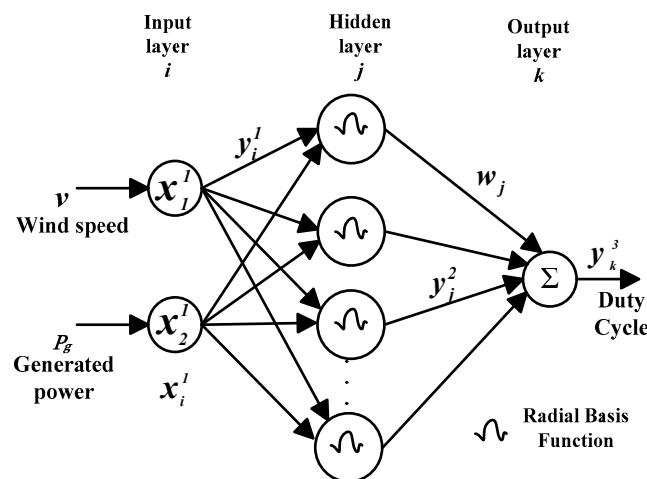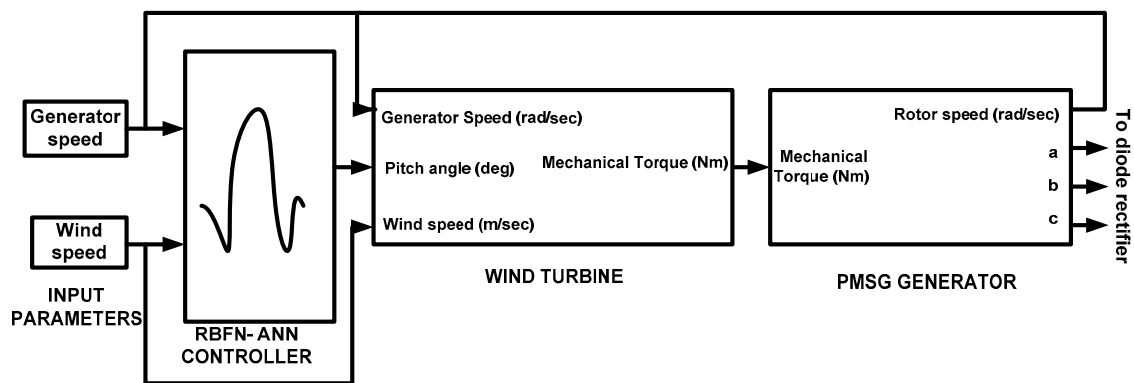

Figure 6. RBFN based MPPT control strategy.

Figure 7. RBFN based pitch angle control strategy.

4. Results and Discussion

To validate the proposed system, the simulation is performed in MATLAB/Simulink for the AEOLOS 3kW wind turbine system. The parameters of AEOLOS 3kW wind turbine and PMSG are given in Table 1. To verify the performance of the coordinated hybrid MPPT-pitch angle control strategy, the simulation is carried out and compared with the control technique employing only the MPPT technique and only the pitch angle control technique when subjected to rapid variations in wind velocity as shown in Figure 8. The rated wind speed considered here is 12 m/s. The performance of the proposed system was validated and compared using the system employing only MPPT and pitch angle control technique as shown in following sections.

Table 1. Parameters of the Aeolos 3 kW system.

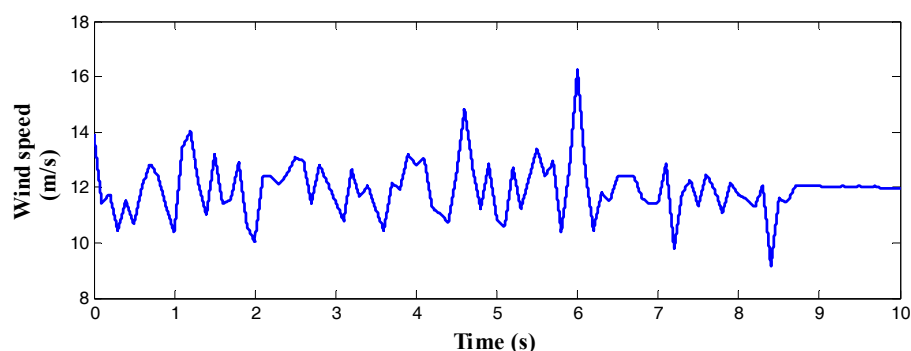| Parameters	Rating
Rated power	3 kW
Rated wind speed	12 m/s
Cut-in win speed	3.0 m/s
Cut-out wind speed	25 m/s
Frequency	50 Hz
Voltage	220–240 V
Rotor diameter	5.0 m
Generator type	Three phase PMSG

Figure 8. Wind speed—Input pattern.

4.1. Only MPPT

The performance of WECS when subjected to wide wind speed region employing RBFN based MPPT control strategy is discussed in this section [26]. The input parameters are the wind speed

and generator power to bring uniformity in the selection of parameters. The WECS comprises the same wind turbine parameters and wind speed as stated earlier. The pitch angle at this operation is kept fixed at $-5°$. The MPPT technique is utilised in both the operating regions (Region 2 and Region 3). In Region 2 where the wind velocity is below the rated value, the MPPT tends to extract the maximum available power at the present wind speed and when the speed surpasses the rated value the MPPT technique optimises the voltage and power to the rated value by adjusting the duty cycle. The performance of the MPPT controller in Region 2 is far better than when compared to Region 3.

Figure 9 shows the DC voltage obtained when the MPPT control strategy is used as the control strategy. As the wind variation is between 9 m/s to 16 m/s the DC voltage obtained is constant. The rated value of the DC voltage is kept as 380 V.
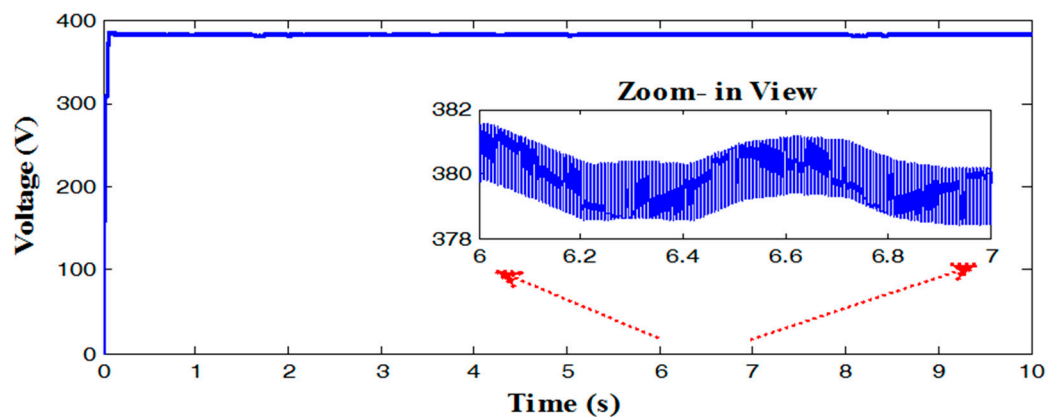

Figure 9. DC voltage—MPPT control strategy.

The maximum power extracted from the available wind speed is shown in Figure 10. The MPPT control strategy can also optimise the power when the wind speed is above the rated speed.
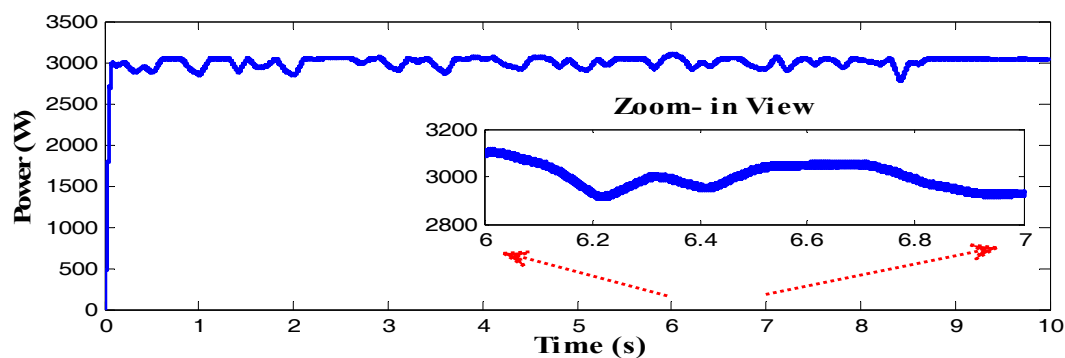

Figure 10. Output power—MPPT control strategy.

The generated power when the wind velocity is above the rated speed is optimised to some extent but still, there is a peak which may increase the turbine stress and damage the system. The PEC associated with the WECS also is designed to withstand up to 5% of the rated value as when there is a sudden hike in the power the whole power electronic components will also be damaged. Thus the wind turbine is subjected to freewheel once the threshold wind speed is obtained thus generating no or very low power during high wind speed conditions. The zoom-in view of the results are also presented between the time range 6 s to 7 s, where the wind input is subjected to sudden gusts in order to validate the performance of the control strategy.

4.2. Only Pitch Angle

The performance of pitch angle control strategy using RBFN control technique is discussed in this section. The input parameters are chosen as wind speed and generator speed. The duty cycle during this strategy is kept constant at an optimum value of 42.1%. The pitch angle control strategy is employed for both the operating regions. In Region 2 the pitch angle control strategy tends to extract the maximum available power from the wind turbine by controlling the power coefficient of the wind turbine. The main application of the pitch angle controller is to optimise the output power beyond the rated power so as to keep the generator producing power in high wind speed conditions. Since the pitch angle is mostly preferred for Region 3, their performance suffers in Region 2. Thus operation of the pitch angle frequently at the all wind speed regions also increases the stress in the system hence the occurrence of break downs is also increased.

Figure 11 shows the output voltage obtained when the pitch angle control strategy is implemented. A constant rated DC voltage of 380 V is obtained at the load despite the high non-linearity.
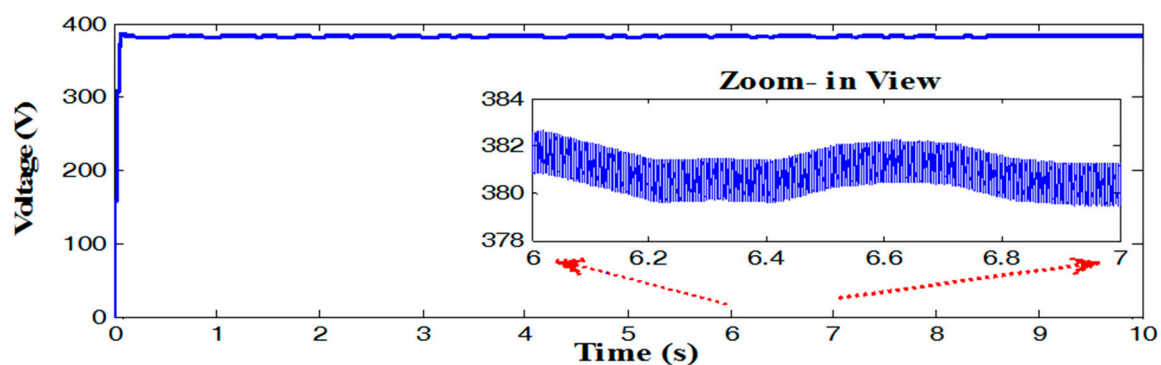

Figure 11. DC voltage—Pitch angle control strategy.

The generated power obtained when the pitch angle control strategy is implemented is shown in Figure 12.The comparison of maximum power obtained when the system is operating in Region 2 is low compared to when MPPT control strategy is used. However, in Region 3, where the system is operating at high wind speed the pitch angle control strategy successfully optimises the output power without any fluctuations or peaking.
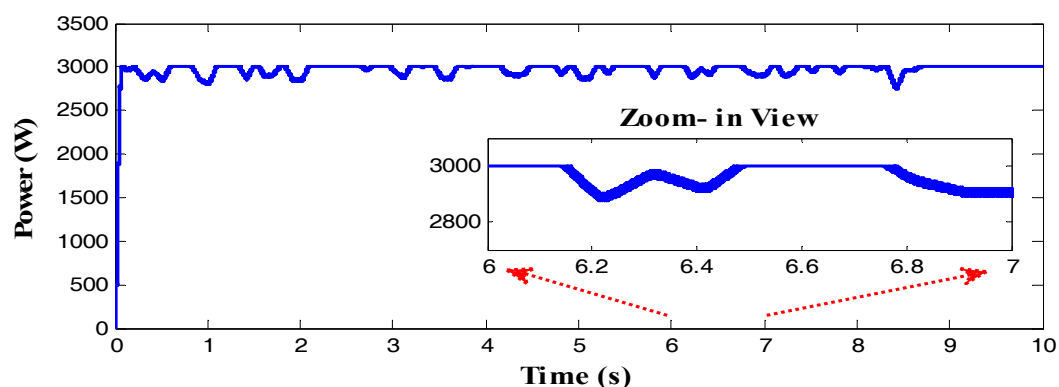

Figure 12. Output power—Pitch angle control strategy.

The pitch angle control strategy when operated to obtain maximum power is subjected to the power coefficient of the turbine. Thus the power coefficient obtained when the pitch angle control strategy operates in the stated system is shown in Figure 13.
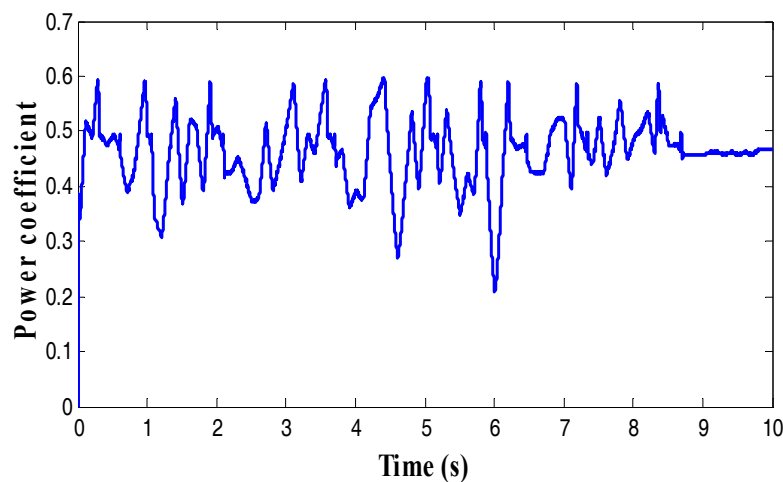
Figure 13. Power coefficient—Pitch angle control strategy.

The performance analysis of the individual controller in the wide wind speed operating region is shown in Table 2. Thus from the analysis, it is observed that to operate the WECS in all wind speed operating regions efficiently it is necessary to develop a new intelligent control strategy.

Table 2. Performance analysis of individual maximum power point tracking (MPPT) and pitch angle control strategy.

Control Strategy	Average Output Power		Average Output Voltage	
	Below Rated Wind Speed	Above Rated Wind Speed	Below Rated Wind Speed	Above Rated Wind Speed
MPPT	2921 W	3097 W	376 V	382 V
Pitch angle	2883 W	3002 W	377 V	380 V

4.3. Proposed Coordinated Hybrid MPPT-Pitch Angle Control Strategy

The proposed control strategy utilises the MPPT control technique when the wind speed is lower than that of the rated wind speed and the pitch angle control strategy when the wind velocity surpasses the rated value. Thus by combining both the control strategies the drawbacks of each individual strategy in maximising and optimising the power can be eliminated. Taking high non-linearity into account, RBFN based ANN control technique can be considered for this technique. The input parameters considered for the proposed technique are wind speed based on which the control technique is decided, generator power to determine the maximum power obtained, and generator speed to obtain the speed of the system in order to optimise it to the rated value. As stated earlier, to fairly evaluate the performance of hybrid control strategy and compare it with the individual control technique the same input parameters are considered. The output of the RBFN based control strategy is the duty cycle for the below rated wind speed condition and the pitch angle for the above rated wind speed condition.

The DC voltage of WECS obtained at the load when the proposed controller is used is shown in Figure 14. The DC voltage which is kept constant at the rated value of 380 V is achieved by using this control strategy. The wind speed variation considered here varies only from 9 m/s to 16 m/s. Thus the rated voltage is obtained and kept constant throughout the operation. In standalone wind systems when the wind speed drops below the transition region (7 m/s in this topology), the rated voltage value also dips. Thus the wind speed should be above the transition value in order to generate a constant DC voltage.
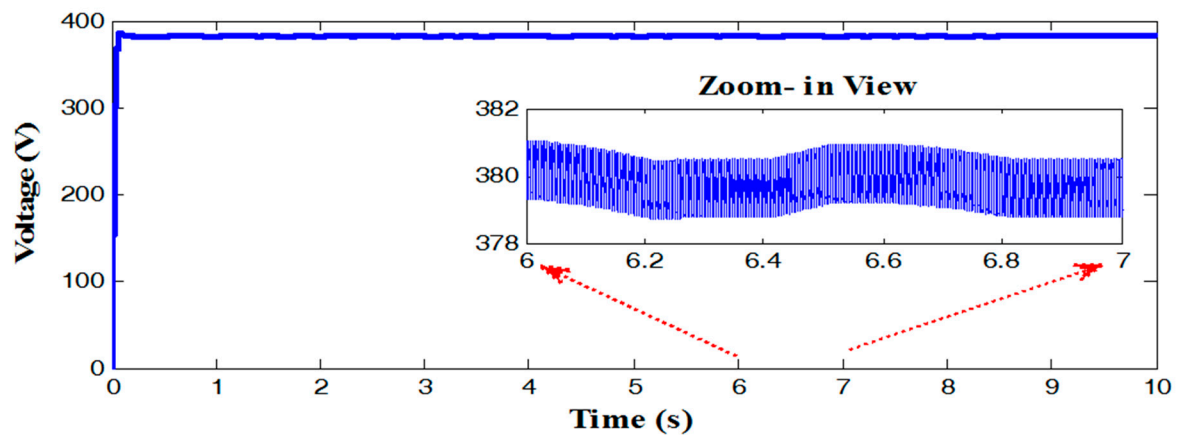
Figure 14. DC voltage—Proposed controller.

The output power which is obtained by using the proposed control strategy is shown in Figure 15. The output power which is achieved in Region 2 is similar to that of the system which uses only MPPT control strategy. Additionally, the output power obtained when operating the WECS in Region 3 is similar to the system which is employed for only pitch angle control strategy. Thus by using the proposed coordinated controller, the performance and efficiency can be enhanced over a wide speed range and prevent the future damage caused by over speeding of the turbine due to high wind speed.
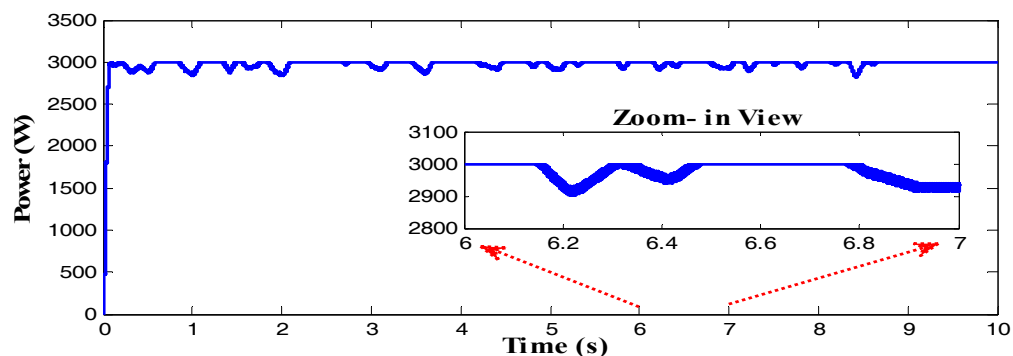

Figure 15. Output power—Proposed controller.

The important parameter which is used to maximise the output power and determine the optimisation of the power in Region 3 is the power coefficient (C_p) which is shown in Figure 16. When the wind speed is lower than the rated wind speed, the generated power is lower than the rated power thus MPPT control strategy is applied in the range of 42.1% to 46.5% for wind speed ranging from 9 m/s to 16 m/s with the pitch angle tuned to $-5°$. Thus the power co-efficient is fixed at 0.456. When the wind speed is higher than that of the rated wind speed (Region 3) the duty cycle of the system is fixed at 42.1% and the optimal pitch angle in the range $-5°$ to $18.4°$ is generated based on the wind speed in order to limit the output power. Region 4 is a no generation region. The WECS produces no power in that region. The optimal power coefficient is obtained using Equation (10) where the corresponding pitch angle is generated using Equation (11).
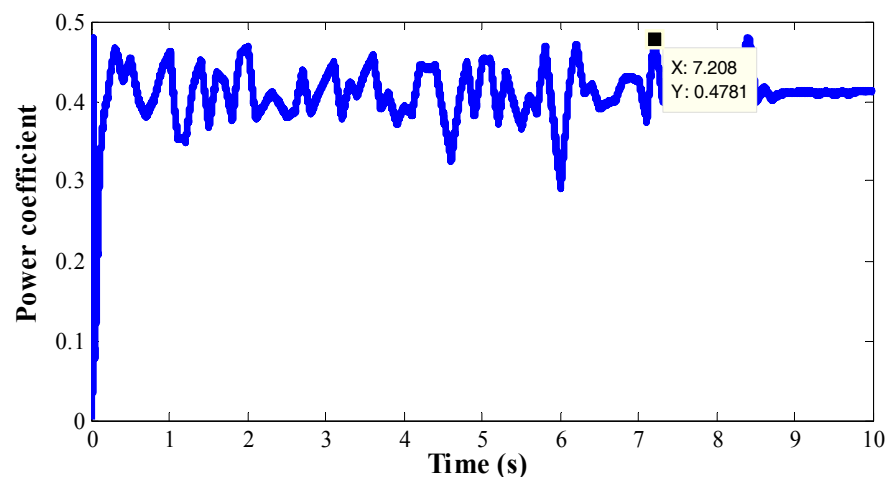
Figure 16. Power coefficient—Proposed controller.

The overall performance of the proposed control strategy is shown in Table 3. The optimum voltage of 380 V is kept as the rated voltage for WECS which is termed as the standard value for the DC microgrid. A rated power of 3 kW is used which is suitable for both standalone and grid connected application.

Table 3. Performance analysis of individual MPPT and pitch angle control strategy.

Control Strategy	Average Output Power		Average Output Voltage	
	Below Rated Wind Speed	**Above Rated Wind Speed**	**Below Rated Wind Speed**	**Above Rated Wind Speed**
Proposed coordinated MPPT and Pitch angle	2943 W	3008 W	376.5 V	381 V

5. Conclusions

In this research, a novel coordinated hybrid MPPT-Pitch angle control strategy employing RBFN based ANN technique for PMSG based WECS was proposed to enhance the overall efficiency of wind power generation in all operating regions. The proposed controller tracks the maximum power when the wind speed is below the rated wind speed and limits the output power in the high wind speed region. To develop the controller, a highly non-linear wind speed input was considered. The wind speed, generator speed, and generated power were selected as the control input variables. The duty cycle and pitch command to the blade were considered as the controlled output variables. The selection of which output variable to be activated is based on the wind speed. In the low wind speed region, the duty cycle is generated to control the power electronics converter thus obtaining maximum available power from the wind speed. When the wind speed exceeds the rated wind velocity, the blade tends to change its angle in order to limit the output power. Thus by using the proposed hybrid control strategy, the output power is maximised with an efficiency of 98.1% compared to 97.3% achieved using an individual MPPT control strategy and 96% using an individual control strategy in below rated wind speed; generator power can be optimised and regulated it the rated value of 3 kW in high wind speed regions. The proposed controller is a suitable alternative for the repowering of small scale WECS, many of which have been installed in developing countries.

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