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Adaptive maximum power point tracking control of wind turbine system based on wind speed estimation

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Abstract

In the variable-speed wind energy system, to achieve maximum power point tracking (MPPT), the wind turbine should run close to its optimal angular speed according to the wind speed. Non-linear control methods that consider the dynamic behavior of wind speed are generally used to provide maximum power and improved efficiency. In this perspective, the mechanical power is estimated using Kalman filter. And then, from the estimated mechanical power, the wind speed is estimated with Newton-Raphson method to achieve maximum power without anemometer. However, the blade shape and air density get changed with time and the generator efficiency is also degraded. This results in incorrect estimation of wind speed and MPPT. It causes not only the power loss but also incorrect wind resource assessment of site.

In this paper, the adaptive maximum power point tracking control algorithm for wind turbine system based on the estimation of wind speed is proposed. The proposed method applies correction factor to wind turbine system to have accurate wind speed estimation for exact MPPT. The proposed method is validated with numerical simulations and the results show an improved performance.

Key words: wind speed estimation, maximum power point tracking, wind turbine system, tip speed ratio, hill climbing search, Kalman filter

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I. Introduction

With the advent of increasing concerns on global energy and environment, renewable energy systems such as wind-energy systems have been finding great attention. Wind energy systems are classified as fixed-speed and variable-speed. Variable-speed systems are beneficial compared to fixed-speed systems for their ability to operate at different wind speeds. Variable-speed system is controlled by angular speed control with power electronic converter thus it produces maximum power and minimizes drive-train loads. MPPT (maximum power point tracking) control allows wind turbine to operate at different speeds with good efficiency [1]-[15].

The purpose of the MPPT is to convert wind energy with a maximum electrical energy in wind turbine system. Several methods exist in literature through which MPPT can be achieved. Typical MPPT control methods of wind turbine system includes TSR (tip speed ratio) control, OTC (optimal torque control) and HCS (hill climbing search). The TSR control method uses speed controller for angular speed of generator by measuring wind speed considering optimal tip speed ratio [2]-[5]. OTC performs MPPT control using parameter K or lookup table which decides the maximum power in wind turbine system with torque controller [3]-[6]. HCS performs MPPT control by deciding the step change that is used as an input according to the change in power and angular speed of generator [3],[5],[7]-[13]. In addition, there are various hybrid MPPT methods depending on wind turbine system to improve the limitations of each MPPT method. To compensate the drawback of HCS method, an algorithm is suggested in [7] by applying HCS to wind turbine system with torque control. A hybrid MPPT algorithm that is computationally fast and is self-tuned with wind speed control as compared to conventional HCS control method is suggested in [12]. An adaptive MPPT algorithm using parameter K which decides the maximum power in wind turbine system with speed control considering micro grid is proposed in [13]. It makes wind turbine control more robust using MPPT mode and non-MPPT mode as compared to conventional MPPT algorithm.

TSR based control considers optimal TSR to achieve maximum power control by regulating the angular speed of generator. For this, estimated mechanical power and angular speed from Kalman filter are used in wind speed estimation using Newton-Raphson method [14],[15]. However, the parameters that are used in control of wind turbine system change for various reasons. For example, air density, generator performance and blade shape [16]. These parameters when are used as fixed values for wind turbine system control it can lead to problems. The changed blade shape, the changed air density and the performance degradation of the generator will lead to inaccurate estimation of wind speed. And also, it leads to power loss in wind turbine system.

In this paper, an adaptive MPPT control algorithm is proposed, which corrects the estimated wind speed to attain more exact MPPT. A correction factor is introduced to consider the changes in blade shape, air density and generator efficiency. The correction factor reduces error in the estimated tip speed ratio thereby estimating the wind speed with better accuracy. Also, maximum power point is tracked. Simulations with constant and variable wind speed are performed using Matlab/Simulink to evaluate the performance of proposed control method.

2. Wind turbine system

2.1 Wind energy

Mechanical power which is theoretically produced by wind energy conversion system is given by [17]

$$P_m = \frac{1}{2}\pi R^2 \rho C_p(\lambda,\beta) v^3 \qquad (1)$$

where R is the die radius of blade, ρ is air density, v is the wind speed, $C_p(\lambda,\beta)$ is power coefficient which depends on tip speed ratio λ and pitch angle of blade β. Tip speed ratio is defined as the ratio of blade tip speed to wind speed v

$$\lambda = \frac{R\omega_r}{v} \qquad (2)$$

where ω_r is angular speed of the rotor. Considering region 2 in the MPPT control, with pitch angle of blade as zero ($\beta = 0$) the mechanical power has the form

$$P_m = \frac{1}{2}\pi R^5 \rho C_p(\lambda) \frac{\omega_r^3}{\lambda^3} \qquad (3)$$

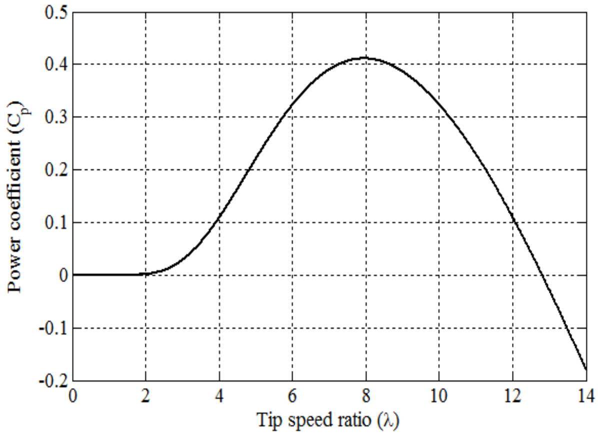

Fig.1. Power coefficient curve according to tip speed ratio

Fig. 1 shows power coefficient according to tip speed ratio for a given blade shape of wind turbine. Power coefficient is maximum value when tip speed ratio is about 7.954. Maximum power coefficient is 0.41096.

2.2 Wind turbine system model

The mechanical energy from the wind is transformed into electrical energy using PMSG (permanent magnet synchronous generator). The topology of PMSG with MSC (machine side converter) is shown in Fig. 2 [13].

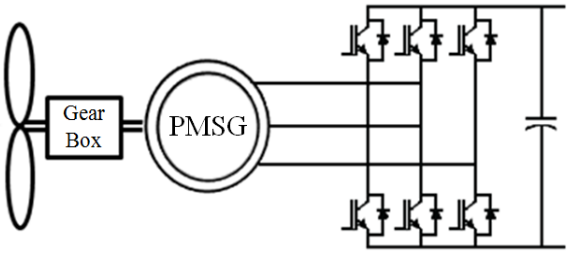

Fig. 2. Drive-train and PMSG system with machine side converter

Wind turbine system control without grid control comprises of gear box, PMSG and MSC as shown in Fig. 2. As the main focus is laid on machine side converter control, grid side converter control is not considered. Voltage equation for IPSMG (interior permanent magnet synchronous generator) model is given by [17]

$$u_d = R_s i_d + L_d \frac{d}{dt} i_d - \omega_e L_q i_q \tag{4}$$

$$u_q = R_s i_q + L_q \frac{d}{dt} i_q + \omega_e L_d i_d + \omega_e \phi_f \tag{5}$$

where u_d, u_q are the generator voltages on the d, q axis, R_s is stator resistance on the d, q axis, i_d, i_q are the currents of the generator on the d, q axis, L_d, L_q are the synchronous inductances of the generator on the d, q axis, respectively, ϕ_f is permanent magnetic flux and ω_e is electric rotating speed that is defined as

$$\omega_e = p\omega_g \tag{6}$$

where ω_g is angular speed of generator and p is pole-pairs of the generator. Electromagnetic torque of IPMSG (T_g) can be calculated from

$$T_g = \frac{3}{2} p i_q \phi_f + (L_d - L_q) i_d i_q \tag{7}$$

Gear ratio n_g is defined as the ratio of mechanical torque T_r of low-speed shaft to the mechanical torque T_m of high speed shaft and it is given by

$$n_g = \frac{T_r}{T_m} = \frac{\omega_g}{\omega_r} \tag{8}$$

The dynamic model of drive-train in wind turbine system is represented by the following equation

$$T_g - T_m = J \frac{d\omega_g}{dt} + B\omega_g \tag{9}$$

where J is equivalent rotational inertia and B is the damping coefficient.

2.3. Estimation of mechanical power using Kalman filter

The response of electromagnetic torque is different from mechanical torque in transient state. The response of electromagnetic torque which can be obtained by (7) is fluctuating than the response of mechanical torque. Therefore, there is need to estimate the mechanical torque with good accuracy. This is achieved using Kalman filter. For applying Kalman filter, dynamic model should be formulated. Using (9), the state-space form for wind turbine system is represented as follows [14],[15]

$$\begin{bmatrix} \frac{d\omega_g}{dt} \\ \frac{dT_m}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{B}{J} & -\frac{1}{J} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \omega_g \\ T_m \end{bmatrix} + \begin{bmatrix} \frac{1}{J} \\ 0 \end{bmatrix} T_g + \begin{bmatrix} 0 \\ 1 \end{bmatrix} w \tag{10}$$

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} \omega_g \\ T_m \end{bmatrix} + \gamma \tag{11}$$

where w is process noise and γ is measurement noise. Using the state-space representation given in (10) and (11) the state parameters, mechanical torque T_m and angular speed of generator ω_g are estimated using Kalman filter. From the estimated state variables, the mechanical power and rotor angular speed are determined by

$$P_{m\_est} = T_m \omega_g \tag{12}$$

$$\omega_{r\_est} = \frac{\omega_g}{n_g} \tag{13}$$

Fig. 3 is block diagram of estimator using Kalman filter. Using estimated torque T_m and angular speed ω_g, estimated mechanical power P_{m_est} and estimated angular speed ω_{r_est} are calculated by (12), (13) which are used for tip speed ratio estimation.

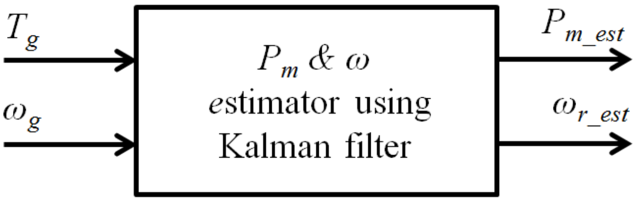

Fig. 3. The block diagram of estimator using Kalman filter

2.4. Tip speed ratio estimation with Newton-Raphson method

Power coefficient curve depends on parameters of the blade shape. Power coefficient of wind turbine is a function of tip speed ratio and blade pitch angle. Here, the blade pitch angle is taken as zero for region 2 therefore the power coefficient can be represented as a function of tip speed ratio alone that is of the form [18],[19]

$$C_p(\lambda) = C_{p0} + C_{p1}\lambda + C_{p2}\lambda^2 + \ldots + C_{pn}\lambda^n \tag{14}$$

where $C_{p0},\ldots,C_{pn}$ are the coefficients of nth-polynomial which can be obtained by interpolation method. Using (14) in (3) and rearranging (3), it can be written as a function of tip speed ratio as

$$f(\lambda) = \frac{P_{m\_est}}{0.5\rho\pi R^5 \omega^3_{r\_est}} - \frac{1}{\lambda^3} C_p(\lambda) = 0 \tag{15}$$

By solving the above equation (15), the tip speed ratio can be obtained. To solve (15), Newton-Raphson method is used which is of the form [14, 15, 19]

$$\lambda_{i+1} = \lambda_i - \frac{f(\lambda)}{f'(\lambda)} \tag{16}$$

Using (15) in (16), tip speed ratio λ is determined iteratively.

2.5. The conventional tip speed ratio control based on wind speed estimation

The conventional tip speed ratio control uses Kalman filter to estimate the mechanical power of generator and the estimated mechanical power is used in Newton-Raphson method to estimate the wind speed to have maximum power point tracking without anemometer [14],[15]. Fig. 4 shows wind turbine control system with MSC based on SVPWM (space vector pulse width modulation). P_{m_est} and ω_{r_est} are estimated by P_m & ω estimator using Kalman filter with T_g and ω_g used as inputs. TSR estimator using Newton-Raphson is then used to estimate tip speed ratio λ_{est}. Considering (2) and (8), estimated wind speed

v_{est} and angular reference speed ω_{ref} are calculated, which are then used as an input for speed controller. The current of the generator is controlled according to switching sequence by SVPWM with two-level IGBT converter [20]-[22].

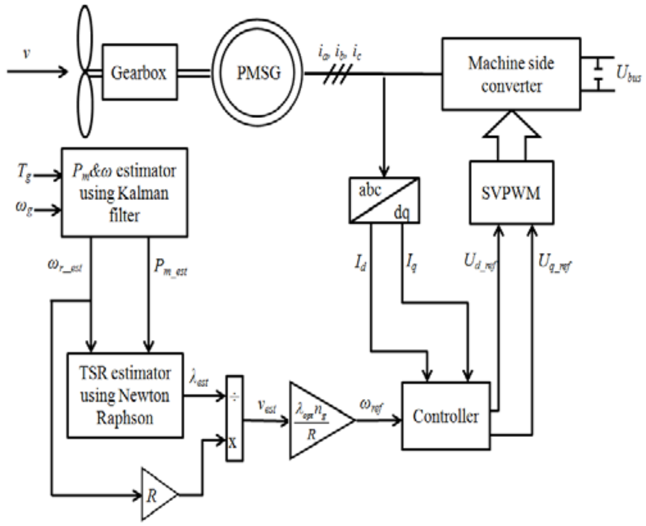

Fig. 4. The TSR controller based on conventional wind speed estimation

3. Adaptive MPPT controller based on wind speed estimation

In the wind turbine system, the parameters such as blade shape, air density get changed with operation time. The generator efficiency is also found to get degraded with time. These affect the accuracy of wind speed estimation. Therefore, adaptive MPPT control algorithm is proposed for improving the accuracy of wind speed estimation. Correction factor is introduced which is determined using hill climb search (HCS). The computed correction factor reduces the error between actual and estimated wind speed. Fig. 5 shows the block diagram for adaptive MPPT algorithm.

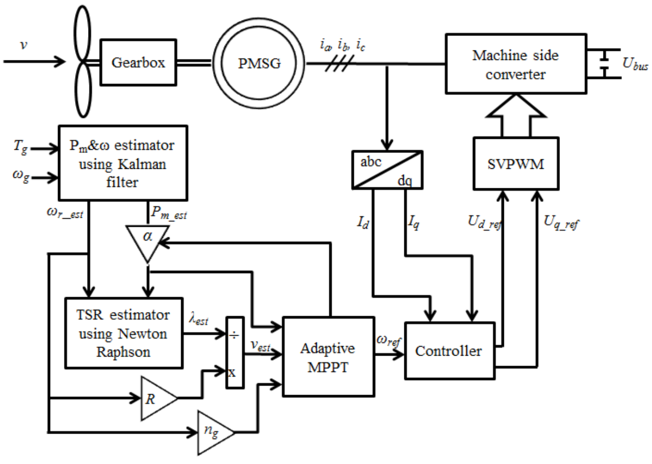

Fig. 5. The adaptive MPPT control algorithm based on wind speed estimation

Correction factor α is added to the conventional tip speed ratio control based on wind speed estimation. From the estimated wind speed v_{est} using Newton-Raphson method, correction factor α is computed in the adaptive MPPT block. The correction factor is then used as an input in TSR estimator to correct the wind speed estimation. From (15), when λ is optimal TSR and $C_p(\lambda)$ is maximum power coefficient, the correction factor which is the reciprocal of efficiency can be represented as

$$\alpha\frac{P_{m\_est}}{0.5\pi R^5\omega_{r\_est}^3 C_{p\_\max}\rho_f}=(\frac{1}{\lambda})^3 \tag{17}$$

where ρ_f is the fixed air density value which is the existing parameter used in traditional wind turbine system based on wind estimation. The correction factor α is defined by

$$\alpha = \frac{1}{\eta_g \eta_b \dfrac{\rho_c}{\rho_f}} \qquad (18)$$

where η_g is the efficiency for performance degradation, η_b is efficiency for the changed blade shape and ρ_c is the current air density.

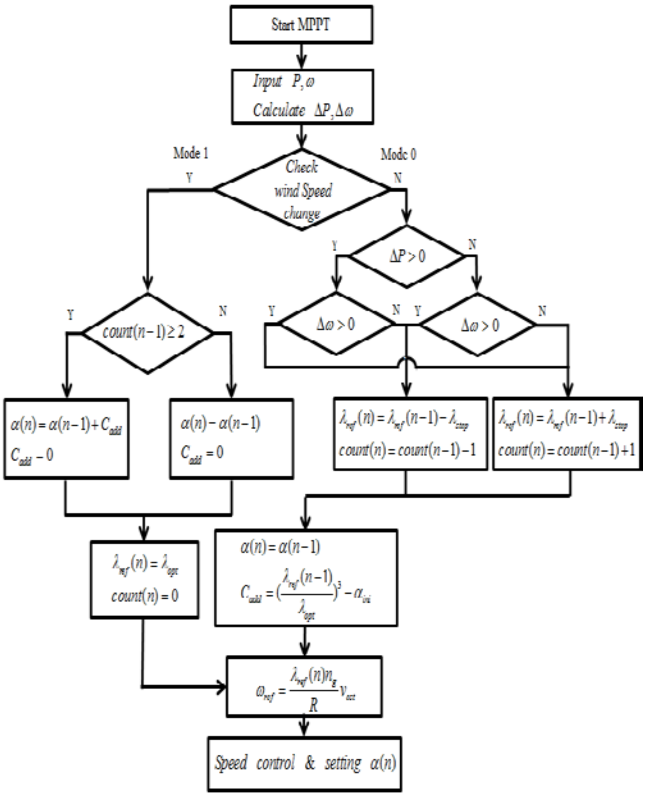

Fig. 6. The adaptive MPPT algorithm based on wind speed estimation

Fig. 6 shows the flow chart for adaptive MPPT algorithm based on wind speed estimation. By checking the wind speed change, mode of operation is decided. When wind speed is changed, MPPT is operated as mode 1. In constant wind speed, MPPT is operated as mode 0. Mode 0 performs HCS method repeatedly by checking ΔP and $\Delta\omega$ to track maximum power point. Using HCS method, λ_{ref} is determined which is then used to compute ω_{ref} for speed controller. In case of change in wind speed, Mode 1 sets λ_{opt} to λ_{ref} and it is used to determine angular reference speed ω_{ref}. When mode 0 is switched to mode 1, λ_{ref} is set as λ_{opt}, $(\lambda_{ref}/\lambda_{opt})^3$ is defined as correction factor α, the parameter C_{add} which is used in updating correction factor α is calculated as

$$C_{add} = \left(\frac{\lambda_{ref}}{\lambda_{opt}}\right)^3 - \alpha_{ini} \qquad (19)$$

where α_{ini} is initial correction factor. In mode 0, the computed parameter C_{add} is added to $\alpha(n-1)$ to get the updated $\alpha(n)$. In mode 1, C_{add} is set as $\mathbf{0}$ for next Mode 0. The updated correction factor $\alpha(n)$ in Mode 1 is then used in wind turbine control system for adaptive MPPT. By applying the correction factor $\alpha(n)$, it is possible to have an accurate estimation of wind speed.

$count(n)$ is used to decide whether to apply correction factor α in mode 1. As HCS is performed in mode 0, when both change in power and angular speed are positive or negative then λ_{step} is added to λ_{ref} and $count(n)$ is increased by 1. Otherwise, λ_{step} is subtracted from λ_{ref} and $count(n)$ is decreased by 1. After that, in mode 1, if $count(n-1)$ is greater than or equal to 2, α is applied to wind turbine system. If $count(n-1)$

is less than 2, α is not applied to avoid unnecessary correction.

The proposed algorithm is to estimate the change in wind speed without anemometer. The evaluation of wind speed change is decided by the following conditions

$$\left|\lambda_{est} - \lambda_{ref}\right| < Err_{\lambda} \tag{20}$$

$$\left|v_{est}(n) - v_{ref}(n-1)\right| < v_{est}^{3} Err_{v}\left(\frac{1}{\alpha(n-1)}\right) \tag{21}$$

where Err_{λ} is allowable error. If (20) and (21) are valid then the wind speed is not changed and is kept constant. However, if the difference in estimated and reference tip speed ratio is greater than the allowable error Err_{λ}, then the wind speed is changed. If actual wind speed is increased, estimated power and estimated wind speed in wind turbine system is increased by equation (1). Here, the noise of estimated power and estimated wind speed is increased according to estimated power and estimated wind speed. For this reason, v_{est}^{3} is used in (21) considering the relationship between wind speed and mechanical power. Moreover, in order to fix the allowable error, $1/\alpha(n-1)$ is used after applying the correction factor α. By considering it, $Err_{v}\left(1/\alpha(n-1)\right)v_{est}^{3}$ is not changed regardless of correction factor α and is just changed according to wind speed.

4. Results and discussion

In this section, numerical simulation results for MPPT control and wind speed estimation are presented. To obtain the simulation results, variable-speed wind turbine system is modeled in Matlab/Simulink.

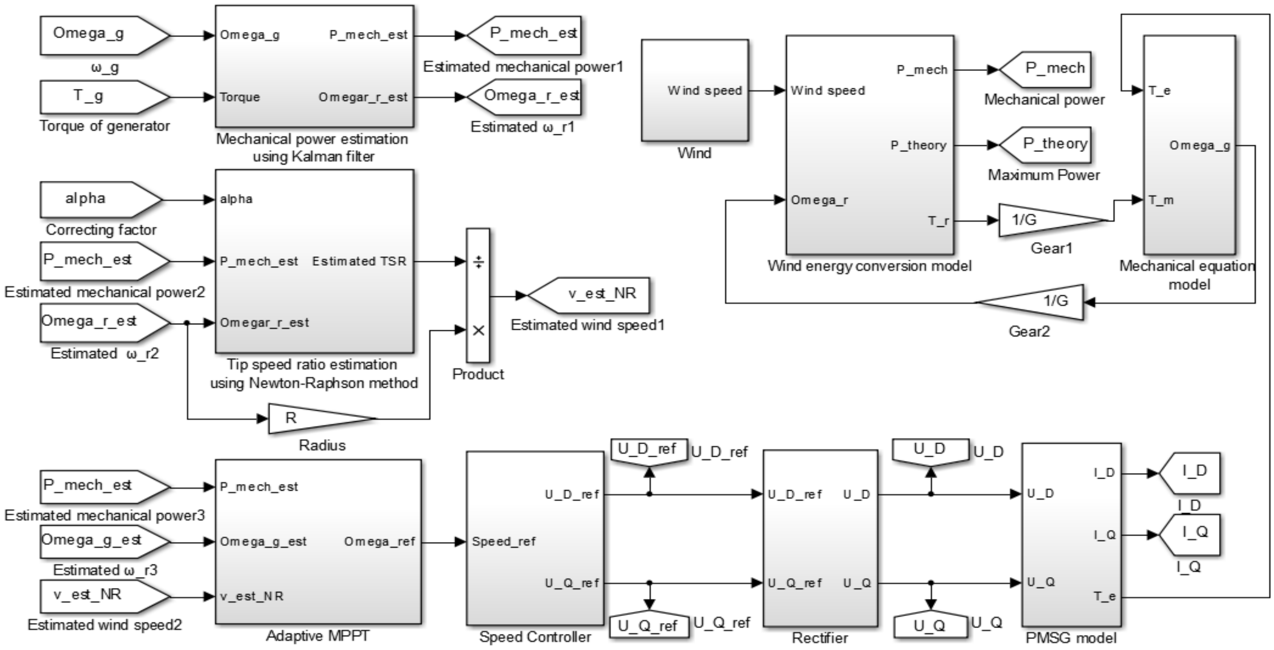

Fig. 7. The adaptive MPPT block diagram based on wind speed estimation in Matlab/Simulink

The Simulink model is shown in Fig. 7. The block diagram of the adaptive MPPT algorithm based on wind speed estimation is composed of mechanical power estimator using Kalman filter, TSR estimator using Newton-Raphson method, adaptive MPPT algorithm, speed controller, rectifier, PMSG model, mechanical model of drive train, wind energy conversion system model and wind speed model. Table 1 has the parameters that are used in simulation of wind turbine system control.

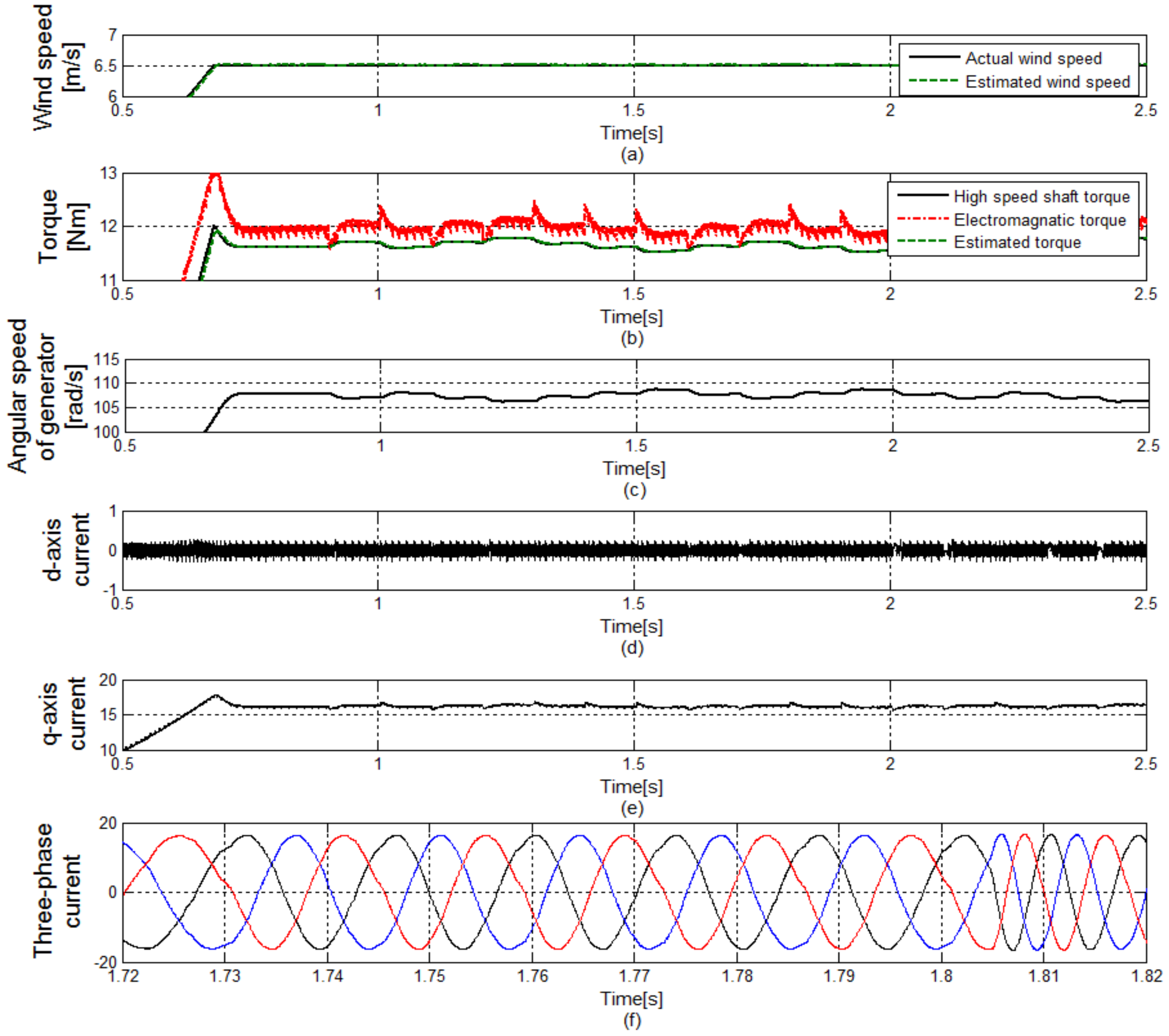

Fig. 8. The performance of estimator with Kalman filter and Newton Raphson method in wind turbine system based on wind speed estimation with SVPWM

The estimator performance based on wind speed estimation with Kalman filter and Newton Raphson method is shown in Fig. 8. The wind speed estimation is shown in Fig. 8(a). It is noticed that the estimated wind speed is tracked close to actual wind speed. Fig. 8(b) shows the estimated torque by Kalman filter with angular speed of generator in Fig. 8(c).

The estimated torque shows dynamic response as high speed shaft torque and is different with electromagnetic torque. By using Kalman filter, input power close to mechanical power is estimated using the proposed algorithm to improve performance. Also, it acts as a filter to reduce the noise and harmonics caused by switching converter control. Fig. 8(d) and 8(e) show the d axis current and q axis current by switching converter control using SVPWM. Fig. 8(f) shows three phase current of generator which d axis current q axis current are transformed to from 1.72 to 1.82 seconds. The current sine wave has distortion caused by harmonics. By wind speed estimation with Kalman filter and Newton Raphson method, MPPT control of Wind turbine system is achieved.

For the simulation, it is assumed that generator efficiency due to performance degradation η_g is 0.98, efficiency for performance degradation of blade η_b is 0.94 and current air density ρ_c is 1.125. In the adaptive MPPT algorithm proposed in this paper, TSR step length λ_{step} which is used in HCS method is set as 0.05 and initial correction factor α_{ini} is set as 1.

4.1. Numerical results

Mechanical power and power coefficient are the amount of energy that is converted from the available wind energy therefore it is considered as standard in evaluating the performance of MPPT control. Fig. 9 shows the performance of the adaptive MPPT control based on wind speed estimation in case of constant wind speed.

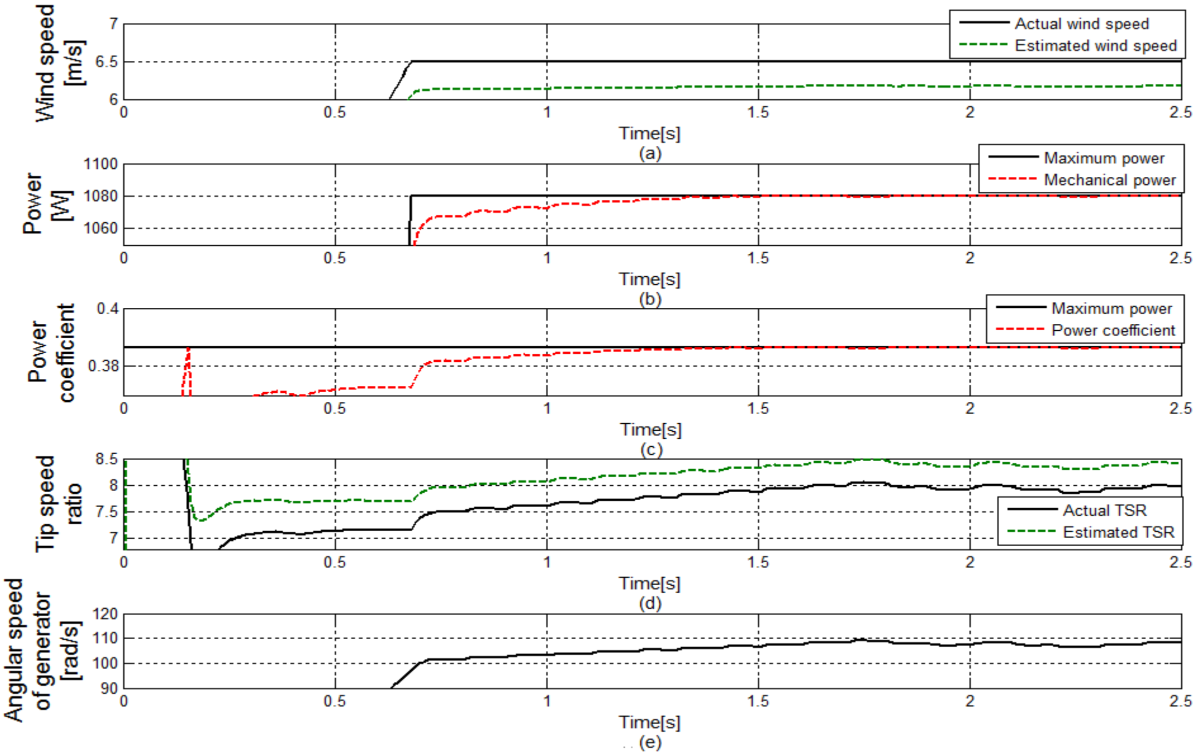

Fig. 9. The performance of the adaptive MPPT control based on wind speed estimation in constant wind

Fig. 9(a) shows comparative result between actual wind speed and estimated wind speed. The maximum power and mechanical power are compared in Fig. 9(b). Fig 9(c) shows power coefficient C_p and maximum power coefficient for constant wind speed. The estimated TSR λ_{est} and actual TSR λ are shown in Fig. 9(d). In constant wind speed, Mode 0 is operated by comparing ΔP and $\Delta\omega$. TSR is found to increase gradually by HCS and remains constant after 0.7 seconds. It can be noticed that mechanical power is able to track maximum power point after 1.4 seconds with estimation of TSR $\lambda_{est} \cong 8.4$ in Fig. 9(b). Power coefficient C_p is also reached to maximum power coefficient in Fig. 9(c). Fig. 9(e) shows that ω_g is changed in wind turbine system according to TSR step λ_{step}. As a result, maximum power point is tracked in 1.4 seconds through HCS method of Mode 0. However, there is still error that exists between the estimated and actual wind speed (Fig. 9(a)). The error is due to the fact that the calculated correction factor α is not updated. Correction factor is applied in Mode 1.

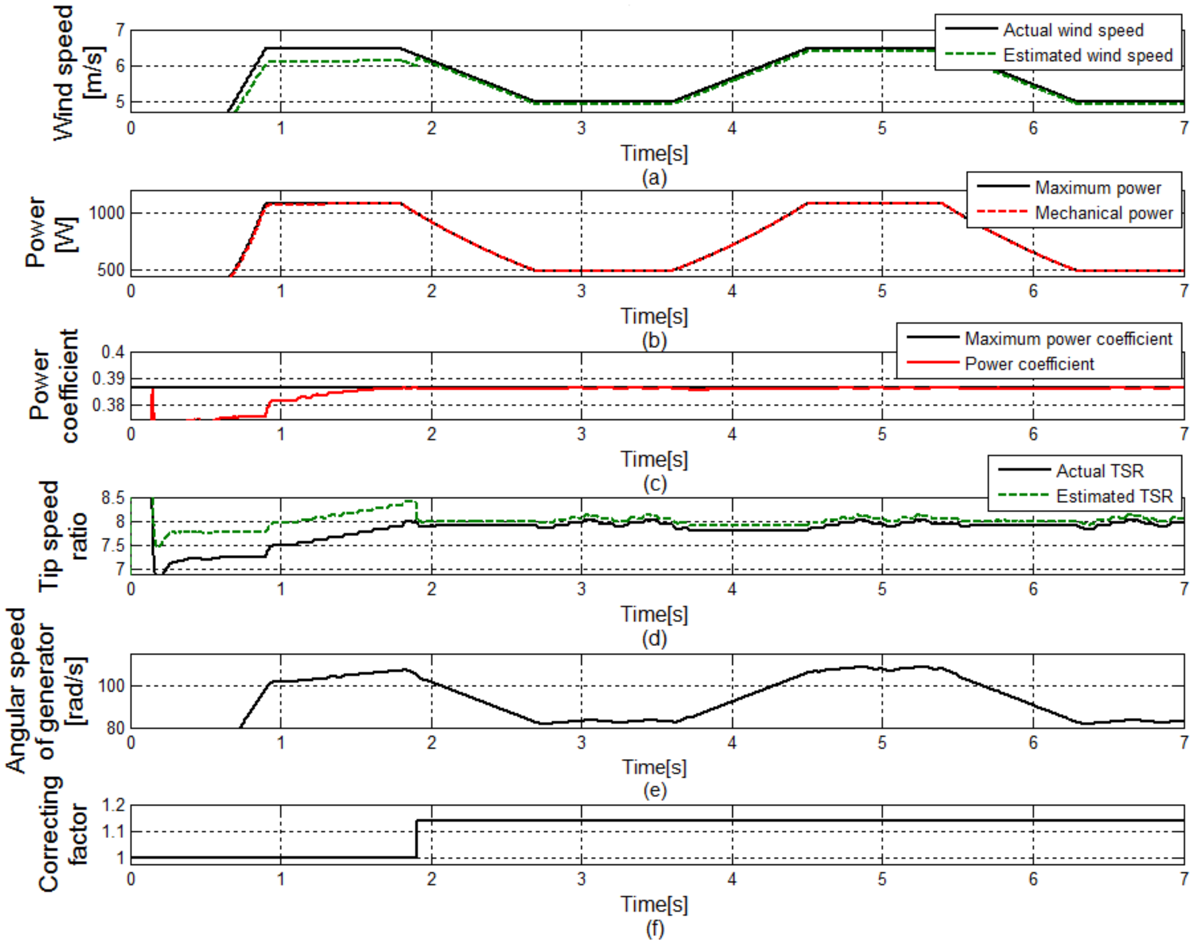

Fig. 10. The performance of the adaptive MPPT control based on wind speed estimation with case 1 wind speed change

Two different cases are considered for the evaluation of proposed method where the wind speed change is considered. Fig. 10 shows the performance evaluation for wind speed change with case 1. From about 1 to 1.8 seconds, reference TSR λ_{ref} is changed by HCS method to track maximum power point. As wind speed is changed in about 1.8 seconds, error between estimated TSR and actual TSR is reduced by applying the calculated correction factor α to wind turbine system as shown Fig. 10(d). The wind speed estimation is found to have tracked the actual wind speed after 1.8 seconds in Fig. 10(a) with correction factor α close to 1.182 in Fig. 10(f). Also, Fig. 10(b) shows that the wind turbine system is controlled as the mechanical power is found to reach maximum power point. Fig. 10(c) shows that power coefficient has reached to maximum power and the performance is improved. The angular speed of generator is detected and is given in Fig. 10(e). Here, relatively small error between actual wind speed and estimated wind speed still exist after 1.8 seconds. The more maximum power point is reached, the more there is not a remarkable change of mechanical power according TSR step. Because, the change in power becomes less as it approaches maximum power (Fig. 9(b)). The above results show that with the proposed method, the wind turbine system has accurate wind speed estimation with more exact MPPT.

Table 1. The parameter of wind turbine system used in simulation [23]

Parameter	Symbol	Value and units
Die radius of blade	R	2.4
Fixed air density	ρ_f	1.225
Rotational inertia	J	0.0048
Damping coefficient	B	0.0030
Gear ratio	n_g	5
d, q axis stator resistance	R_s	0.180
d axis synchronous inductance	L_d	0.002
q axis synchronous inductance	L_q	0.002
Permanent magnetic flux	ϕ_f	0.123
Pole-pairs of the generator	p	4

Fig. 11 shows that the performance of the adaptive MPPT control based on wind speed estimation for changed wind speed with case 2. When an actual wind speed is changed as shown Fig. 11(a), mechanical power and angular speed of generator are changed in Fig

11(b) and Fig. 11(e). Fig.11(c) shows that power coefficient is changed over time. Fig. 11(d) shows estimated TSR and actual TSR are changed by the proposed algorithm. Fig. 11(f) shows the change of correction factor, which is calculated in mode 0 and applied to mode 1. Although there is error between estimated TSR and actual TSR at the beginning, with α close to 1.182 obtained in 20 seconds, the estimated TSR is almost close to the actual TSR. Also, the estimated wind speed is found to approach the actual wind speed and it is tracked well after 20 seconds. Also, power coefficient is reached to maximum power coefficient in 20 seconds. From the simulation studies, it was noticed that the adaptive MPPT control estimates the wind speed exactly thereby controls the wind turbine to achieve more exact MPPT.

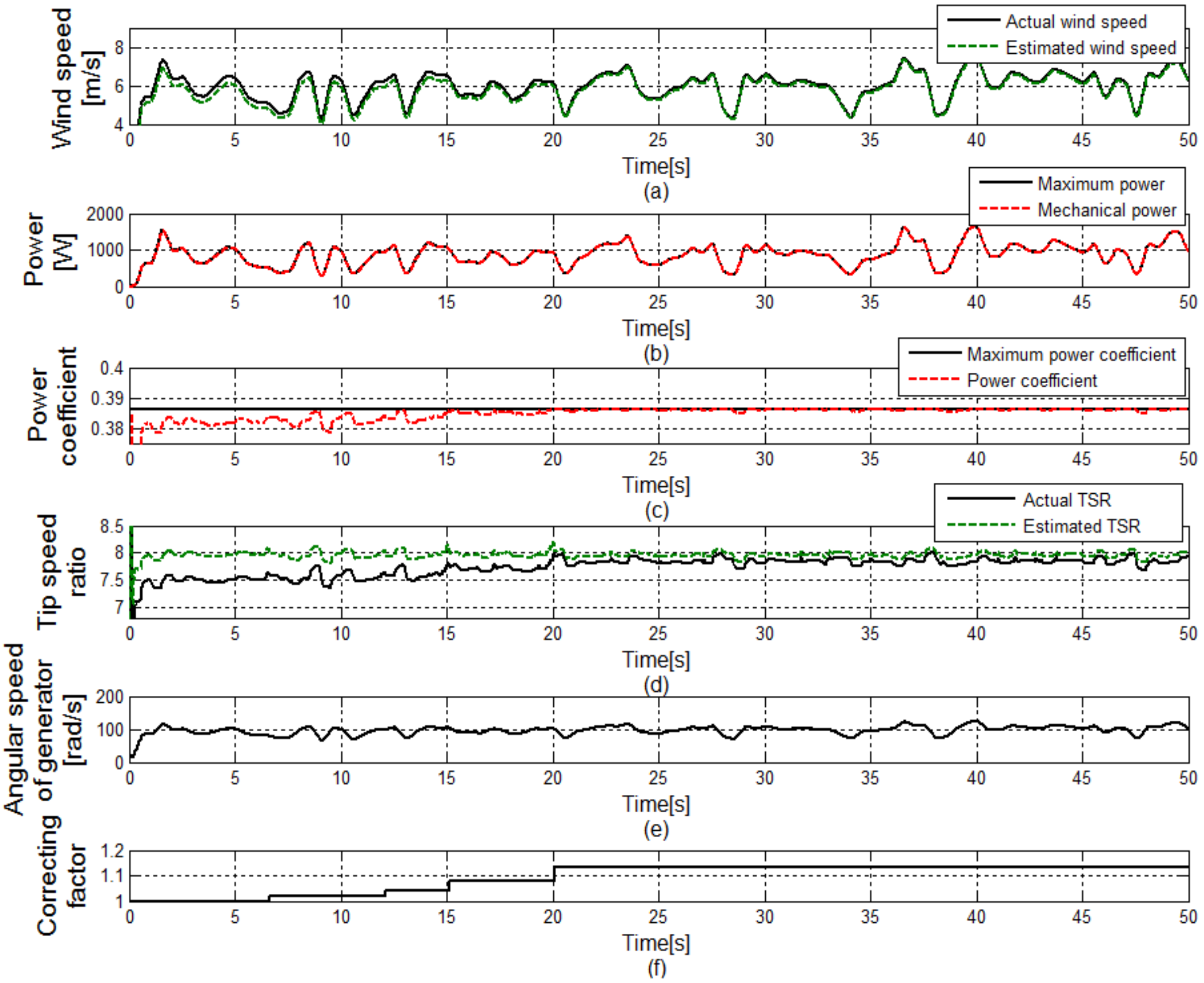

Fig. 11. The performance of the adaptive MPPT control based on wind speed estimation in case 2 wind speed change

5. Conclusion

Because of the changed blade shape, changed air density, and performance degradation of the generator, conventional TSR control based on wind speed estimation not only causes the problem for MPPT but also estimates incorrect wind speed. It leads to inexact wind resource assessment of site. To solve this problem, the adaptive MPPT control based on wind speed estimation in wind turbine system is proposed. In this paper, the adaptive MPPT control algorithm is developed considering wind turbine system with machine side converter control. The proposed algorithm applies the updated correction factor to adaptive MPPT control. The adaptive MPPT control is performed properly by tracking maximum power point. Furthermore, as the error between estimated and actual tip speed ratio is reduced, more exact wind speed is estimated. Simulation studies with Matlab/Simulink are performed with constant and variable wind speed. The results show that the adaptive MPPT control has better estimation of wind speed from the correction factor that is computed.

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