Abstract

Even though hill climbing search (HCS) control is the simplest MPPT algorithm that does not require any prior knowledge of the system, it has the disadvantage of being slow in its response. This slowness in the response is due to the number of perturbations involved in climbing the hill and the settling time of each perturbation. This paper proposes an improved HCS control, in which the nature of the input perturbation is changed, so as to improve the control algorithm’s response speed in tracking the maximum power point of a wind turbine.

1 Introduction

Variable speed wind turbines offer many advantages over those of fixed speed type such as increased aerodynamic efficiency below rated wind speed, less aerodynamic noise, improved power quality and load reduction possibility [7] [3]. These advantages outweigh the additional cost and complexity resulting from the indispensable power converters required to interface the generator and the grid. The use of Permanent Magnet Synchronous Generator (PMSG) in variable speed turbines is increasing because of their high efficiency due to the absence of rotor winding, high power density and the possibility of eliminating the gear box by designing low speed PMSG with increased number of poles.

The variable speed wind turbine has to operate at or the near the maximum power point on the turbine characteristic curve to achieve maximum efficiency at or below the rated wind speed. Therefore maximum power point tracking (MPPT) is essential for maximising energy extraction, thereby minimising the pay back period of the investment involved. In the general context of wind electric system (WES), the conventional MPPT techniques can be classified into three categories viz. Tip Speed Ratio (TSR) control [5], Power Signal Feedback (PSF) control [8] and Hill Climbing Searching (HCS) control [9] [1]. The first two techniques are essentially based on look-up tables, generated with offline prototype/design data. In TSR control, based on predetermined optimal tip speed ratio vs. wind speed characteristics, the generator reference speed is calculated from current wind speed measurement. In PSF control, a mapping function/look-up table with stored values of optimal turbine power vs. generator speed is used to set the output power reference for the turbine.

In contrast, the HCS control does not require any a-priori characterization of the primary energy conversion process and is widely used in photovoltaic (PV) based generation systems. In this application, the HCS approach ensures acceptable tracking speed chiefly due to the small inertial components, which are exclusively electrical, and slow variations in the energy input. However, this is a critical limitation when applied to WES where input power variations are much larger and faster in comparison. Also, the system inertia, which is chiefly mechanical, is orders of magnitude larger than that in PV systems. This implies a larger settling time, with realistic control effort, following a perturbation in its reference command. For a given single perturbation step size, time taken to reach the maximum power point (MPP) is the product of the number of perturbation steps and settling time associated with each step. Settling time, decided by the controller and system parameters, is not only limited by the over current limits of the electric generator and power converter but also by the allowable transient over/undershoots in the output power. Reducing the number of perturbations, by increasing the perturbation step magnitude, imply loss of resolution and large limit cycles around the MPP. So the scope for improvement in the speed of algorithm convergence is rather restricted.

In this paper, the nature of the perturbation is changed from step function to ramp function during certain intervals which improves the speed of the algorithm significantly. After the initial settling time in this interval where the speed is changing in ramp form, the information of power increase/decrease can be obtained with very little time steps compared to conventional HCS algorithm since the system is already in pseudo-steady state as shown in the paper. In this way the power coefficient undergoes a rapid increase in this interval resulting in faster algorithm.

2 WES Modelling

The configuration of the WES used in this paper is shown in Figure 1. It consists of a wind turbine, a PMSG with multiple poles and back to back voltage source converters.
(VSCs) with inductive filters. In this section the mathematical modeling of the WES components is presented.

2.1 Wind Turbine

The amount of mechanical power captured by a wind turbine from the wind is a function of the area \( A \) swept by its blades, air density \( \rho \), the incoming wind velocity \( \upsilon \) and its conversion efficiency \( C_\lambda \). The conversion efficiency or power coefficient of a turbine \( C_\lambda \) is a function of the tip-speed ratio \( \lambda \) and pitch angle \( \beta \).

\[
P_m = \frac{1}{2} \rho A \upsilon^3 C_\lambda(\lambda, \beta)
\]

where, \( \lambda \) is the ratio of the tip speed of the turbine blades to wind speed. Mathematically,

\[
\lambda = \frac{\omega_m R}{\upsilon}
\]

where \( \omega_m \) is the turbine rotational speed in mechanical radians/second and \( R \) is the radius of the turbine in meters. While extracting the maximum power from the turbine, the value of the pitch angle \( \beta \) is kept constant (around 0\(^\circ\)), to ensure maximum possible turbine output. In this case, \( C_\lambda \) depends only on \( \lambda \) and can be expressed as a polynomial function of the form

\[
C_\lambda = \sum_{i=0}^{6} a_i \lambda^i.
\]

where the coefficients \( a_0 \) to \( a_6 \) are listed in Table 1. The \( C_\lambda \) vs. \( \lambda \) characteristics are as depicted in Figure 2.

2.2 PMSG with inductive filter: Modelling

The dynamic model of the PMSG is expressed in an orthogonal reference coordinate system, rotating synchronously with the rotor magnet flux. Spatial distribution of the flux established by the permanent magnets along the air-gap is considered to be sinusoidal. The \( d \)-axis of the synchronously rotating reference frame is aligned with the rotor flux, with the \( q \)-axis leading. Since the relative permeability of the permanent magnet is close to unity, for a surface-mounted machine, the effective air gap and hence the reluctance between stator and rotor surface is fairly constant. The machine equations [6] are

\[
v_{sq} = i_{sq} R_t + L_s \frac{di_{sq}}{dt} + \frac{P}{2} \omega (\psi + L_t i_{sd})
\]

\[
v_{sd} = i_{sd} R_t + L_s \frac{di_{sd}}{dt} - \frac{P}{2} L_t \omega i_{sq}
\]

where,

- \( P \) is the pole number,
- \( v_{sd}, v_{sq} \) are the stator voltages and \( i_{sd}, i_{sq} \) are the stator currents in \( d - q \) reference frame,
- \( R_t \) is the total resistance of the stator winding and filter inductance,
- \( \psi \) is the rotor magnetic flux linkage, and
- \( (P/2)\omega \) is the generator electrical frequency.

The electromagnetic torque developed by the PM machine (generator) is given by

\[
T_e = \frac{3}{4} P \psi i_{sq}
\]

and the dynamics of the mechanical system is expressed as

\[
\omega = \frac{1}{J} \int (T_m - T_e - B \omega) dt
\]

where \( J, B \) are the equivalent moment of inertia and friction coefficient of WES, \( T_m, T_e \) are mechanical and electromagnetic torques respectively.

3 Proposed MPPT algorithm

The proposed MPPT algorithm operates in two distinct modes, namely, the ramp mode in addition to the conventional HCS mode. Rapid acceleration towards the MPPT is ensured in the ramp mode through intelligent control of the generator torque and subsequently slow vernier convergence is brought about by the HCS routine. Changeover from the ramp to HCS mode occurs immediately when MPP is marginally overshot, the vernier mode is thus required for a short interval. The algorithm starts with the usual speed perturbation as in a conventional HCS routine.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
<th>Coefficient</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_0 )</td>
<td>0.0001947</td>
<td>( a_4 )</td>
<td>0.02607</td>
</tr>
<tr>
<td>( a_1 )</td>
<td>-0.01844</td>
<td>( a_5 )</td>
<td>-0.00457</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>0.07632</td>
<td>( a_6 )</td>
<td>0.0002633</td>
</tr>
<tr>
<td>( a_3 )</td>
<td>-0.06047</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: coefficients of \( C_\lambda \) expression.
Table 2: Parameters of the WES.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbine</td>
<td></td>
</tr>
<tr>
<td>Rated power</td>
<td>10KW</td>
</tr>
<tr>
<td>Radius of the turbine</td>
<td>2.677</td>
</tr>
<tr>
<td>PMG</td>
<td></td>
</tr>
<tr>
<td>Rated voltage</td>
<td>490 V</td>
</tr>
<tr>
<td>Rated power</td>
<td>10 kW</td>
</tr>
<tr>
<td>Number of poles</td>
<td>24</td>
</tr>
<tr>
<td>Rated rotor speed</td>
<td>22 rad/sec</td>
</tr>
<tr>
<td>Stator inductance and resistance</td>
<td>13.47 mH, 0.63 Ω</td>
</tr>
<tr>
<td>Filter inductance</td>
<td>50 mH</td>
</tr>
<tr>
<td>DC link Voltage</td>
<td>800 V</td>
</tr>
<tr>
<td>Moment of inertia</td>
<td>30 kg-m</td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>5 N-m/(rad/sec)</td>
</tr>
<tr>
<td>Air density</td>
<td>1.205 kg/m³</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>6 KHz</td>
</tr>
<tr>
<td>Controller Parameters</td>
<td></td>
</tr>
<tr>
<td>$K_{1i}$</td>
<td>10</td>
</tr>
<tr>
<td>$K_{2i}$</td>
<td>450</td>
</tr>
<tr>
<td>$K_{1s}$</td>
<td>480</td>
</tr>
<tr>
<td>$K_{2s}$</td>
<td>1920</td>
</tr>
</tbody>
</table>

However, when a perturbation results in large output power change, the MPPT algorithm enters the ramp mode. In the ramp mode, the machine reference speed is ramped up (down) with a pre-defined constant time-rate. If the ramp mode is selected at the $k^{th}$ instant, direction of this ramp, $\alpha^r(t)$, is decided as

$$\text{sgn}(\alpha^r) = \text{sgn}(P[k] - P[k-1]) \times \text{sgn}(\omega[k] - \omega[k-1]).$$  \hspace{1cm} (8)

where $\text{sgn}$ denotes the signum of the respective quantities.

To decide the ramp slope, which physically translates to the reference acceleration $\alpha$, Equation (7) is first expressed as a differential equation and the corresponding power equation is

$$P_m - P_e = \omega(T_m - T_e) = \omega J \frac{d\omega}{dt} + B\omega^2.$$ \hspace{1cm} (9)

Magnitude of the reference acceleration ($\alpha^r$) is decided based on the available power at the instant of the entering the ramp mode. In the ramp mode, Equation (9) is expressed as

$$P_m - P_e = \omega J \alpha + B\omega^2$$ \hspace{1cm} (10)

differentiating which with respect to $\omega$,

$$\frac{dP_m}{d\omega} - \frac{dP_e}{d\omega} = J\alpha + 2B\omega.$$ \hspace{1cm} (11)

The speciality of Equation (11) is that it is valid only in the speed transient region ($P_m \neq P_e$) and is not defined in steady-state. This is because Equation (11) can be expressed as

$$\frac{d}{d\omega}(P_m - P_e) = \left\{ \frac{d}{d\omega}(P_m - P_e) \right\} / \left\{ \frac{d\omega}{dt} \right\}$$ \hspace{1cm} (12)

where the right hand side is undefined in steady-state. Using Equation (11) and Equation (12), the time-rate of the accelerating power, in the speed-transient region, evaluates to

$$\frac{d}{d\omega}(P_m - P_e) = \alpha^2 J + 2B\omega \alpha.$$ \hspace{1cm} (13)

Since the accelerating torque ($\alpha J$) is much larger than the friction torque ($B\omega$) in a well-designed turbine-generator, it is obvious that maximum of $P_e$ occurs prior to that of $P_m$. Also, if the speed control loop ensures accurate reference tracking, the closeness of the maxima of $P_m$ and $P_e$ in the speed-transient region is decided by the choice of the ramp slope, $\alpha^r$. So, from Equation (11), if the accelerating power is small compared to the maximum $P_m$, then the speed at which $(dP_e/d\omega)$ equals zero is close to the speed at which the value of $(dP_m/d\omega)$ becomes zero.

The ramp mode ends at the speed when a change of sign in $(dP_e/d\omega)$ is detected and the algorithm effects a changeover to the conventional HCS mode. Since the peak of the $P_m - \omega$ curve is closer to the operating point at this speed, the value of $C_p$ is also close to its maximum $C_p_{\text{max}}$. Hence the conventional HCS mode can be used with smaller speed perturbations resulting in smaller limit-cycles around the MPP. The parameters involved in the proposed algorithm can be suitably tailored to increase the efficiency without compromising tracking speed. The flowchart of the proposed MPPT algorithm is given in Figure 3.

4 WES Control

In Figure 1, the machine side VSC extracts power from the turbine-generator, according to the proposed algorithm, while the grid side VSC regulates the DC link voltage, thereby delivering the extracted power to the utility grid. In this paper, controller for the grid side VSC is assumed to ensure the DC link voltage is maintained at its rated value. Since the operation of the grid-side VSC is outside
the scope of the focal theme, its operation is not considered any further. Figure 4 shows the basic control structure of the machine side VSC of the WES. The MPPT algorithm provides the reference speed to be tracked by the drive train of the system. A vector control strategy is used to control the speed dynamics of the PMSG where the q-component of the stator current is used to control the electromagnetic torque. The d-axis component is set at zero to minimise the resistive losses [4]. As shown in the figure, there are three control loops present in the vector control strategy, a speed control loop with an inner torque/q-axis current loop and a d-axis current loop. Controller design for these three loops is presented below. The plant transfer function for both inner current loops is given by

\[ G_i(s) = \frac{i_d(s)}{v_d(s)} = \frac{i_q(s)}{v_q(s)} = \frac{1}{R_t + L_t s} \]  

(14)

A PI controller in frequency domain is designed to ensure a maximum settling time of 50 ms and is given by Equation (15).

\[ H_i(s) = K_{1i} + \frac{K_{2i}}{s} \]  

(15)

and the corresponding magnitude and phase plots are shown in Figure 5. The cross-over frequency of the current control loop is 164 rad/sec and the phase margin is 81°, which implies high relatively stability and a close-loop settling time of about 25 ms.

The transfer function of the outer speed loop is decided by the mechanical dynamics and is

\[ G_s(s) = \frac{1}{Js + B} \]  

(16)

Numerical value of the friction coefficient \(B\) considered corresponds to a aggregated mechanical loss of 1% at rated condition. All A PI controller is designed to ensure a maximum settling time of 0.5 s and is given in Equation (17). The corresponding magnitude and phase plots are shown in Figure 6. The cross-over frequency of the speed control loops is 16 rad/sec and the phase margin is 77°. This ensures a settling time of about 0.25 s and assured stability as well as zero steady-state error in closed-loop operation.

\[ H_s(s) = K_{1s} + \frac{K_{2s}}{s} \]  

(17)

All system and controller parameters are listed in Table 2.

![Figure 4: Vector control of PMSG.](image)

![Figure 5: Bode magnitude and phase plot of current control loop transfer function.](image)

![Figure 6: Bode magnitude and phase plot of speed loop transfer function.](image)

5 Simulation results & discussions

The WES is simulated using MATLAB/Simulink, with the proposed algorithm as well as with an exclusively conventional HCS approach. In both cases the wind speed is changed from 9 m/s to 12 m/s at 11 s and from 12 m/s to 10.5 m/s at 18 s. The wind profile, power coefficient \(C_p\) obtained and harvested energy with both approaches are shown in Figure 7. It shows that the proposed method helps to reach the vicinity of the MPP much earlier than the conventional HCS approach. The harvested energy shows the trend of the difference in harvested energy from the two approaches, the proposed method resulting in larger energy extraction even within the small time interval under consideration. With subsequent wind-speed variations, these curves further separate, demonstrating better performance by the proposed approach.

The reference and the actual speeds in both the cases are shown in Figure 8. In both cases, the power coefficient reaches its maximum value 0.4 after every change in wind speed.
From Figure 8 it is observed that, at 0.5 s, the proposed algorithm enters the ramp mode and the speed continues to increase till the power coefficient reaches around 0.38. Thereafter it enters the conventional HCS mode with a small perturbation step of 0.15 rad/sec which moves the operating point close to MPP. For comparison with an exclusively conventional HCS algorithm, a much larger speed step of 0.45 rad/sec is used. The speed steps in the conventional HCS mode in the proposed approach as well as in exclusively conventional HCS algorithm are identically decreased gradually while approaching MPP to anneal the limit cycles \([10]\). It is evident that the proposed algorithm converges significantly faster as compared to the exclusively conventional HCS algorithm.

The power at the terminals of the PMSG, the wind turbine power, the reference and actual speeds for the proposed algorithm are shown in Figure 9. It clearly shows that during ramp mode, the generator terminal power \((P_e)\) is different from the turbine power \((P_m)\) ensuring speed-transient operation. Thus, during the entire ramp mode operation steady-state is not attained, hence the basic analytical premise of the ramp mode is not violated. The accelerating power \((P_m - P_e)\) is also observed to be positive during positive wind-speed steps and negative during the transient after a fall in wind-speed. This decides for the energy taken during acceleration or released during deceleration of the rotating parts. By changing the ramp slope, \(\alpha^*\), it is possible to control the accelerating power. Choice of this parameter is somewhat involved since a large ramp-slope, while reducing the duration of the ramp mode, separates the dynamic maxima of the mechanical and electrical powers. This increases the speed interval to be bridged by the vernier mode which obviously reduces tracking speed. Also, a large \(\alpha^*\) results in large over/undershoots in the generator terminal output power during ramp mode. However, an unilateral decrease in \(\alpha^*\) leads to a drastic reduction in MPP tracking speed. In this paper, 30 % of the available power at the starting of the ramp mode is used to accelerate the rotating parts, as shown in the flowchart given in Figure 3.

### 6 Conclusion

In this paper, an improved MPPT algorithm is presented, with reference to WES. The presented algorithm introduces a fast ramp mode followed by a slow vernier mode, which is similar to a conventional HCS algorithm. Theoretical basis for the proposed approach is clearly explained and relevant interpretations made within a premise of speed-transient operation. Numerical simulation results are presented for a low power WES where the performance of the proposed method is shown to be significantly superior than conventional HCS algorithm in terms of tracking speed and harvested energy. It is also shown that the premise of transient
speed, which is necessary for the validity of the theory underly-
ing ramp mode operation, is also not violated for any magnitude and direction of change in wind speed. Although a low-power system has been considered here, applicability of the proposed approach can be directly extended to installations with larger ratings.

References


