Backstepping nonlinear control to maximize energy capture in a variable speed wind turbine

Ouadia El Maguiri¹, Driss Moussaif², El alami Smma³, Farchi Abdelmajid⁴, Aziz Akhiate⁵
¹²³⁴IMII-lab, Faculty of Science and Technology, University Hassan 1st, Morocco
²³RLSEISE-lab, University of Hassan II, ENSAM, Morocco

ABSTRACT

We are considering the problem of maximum power point tracking MPPT in wind energy conversion system (WECS). The paper proposes a new control strategy to maximize the wind aerodynamic energy captured in variable speed wind turbine with a separately excited DC-Generator and transformed to the battery through a controlled DC-DC converter. The proposed strategy controls the stip speed ratio via the rotor angular speed to an optimum point at which the power coefficient is maximal. The controller is designed using the backstepping technique. A formal analysis based on lyapunov stability is developed to describe the control system performances. In addition to closed-loop global asymptotic stability, it is proved that the controller actually meets the MPPT requirement. The above results are confirmed by simulations.

Keywords:
Backstepping control
DC-DC converter
DC generator
Lyapunov stability
MPPT

1. INTRODUCTION

In isolated places where no electric grid is available, wind turbines generators (WTG) and photovoltaic (PV) arrays are used to provide electricity. However intermittent characteristic of solar and wind energy creates a need for energy backup. Battery charging is an interesting alternative because of its simplicity and reliability [1-2].

As shown in Figure 1, battery charging application often use a generator that converts wind turbine power to output voltage and a DC-DC converter on its various topologies Buck, Boost, Buck-Boost [3] and resonant DC/DC converter [4]. Generally the DC generator is a good choice for a (WTG) as it is simply to control and its dynamic characteristics are very good [5]. On another hand, there is a considerable interest in using variable speed wind turbines. Indeed, these can be driven constantly near to the optimum tip-speed ratio \( \lambda_{opt} \) through turbine rotor speed control as shown in Figure 1. Specifically, rotor speed must follow wind-speed variations in low and moderate velocities in order to maximize aerodynamic efficiency. This scheme is known as maximum power point tracking (MPPT) [6].

The Wind generators power production can be mechanically controlled by changing the blade pitch angle [7]. However, (WTG) of special construction are required, which is not the usual case, especially in small-size stand-alone wind energy conversion systems (WECS).
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The polynomial approximation for $cp$ can be expressed as

$$cp(\lambda) = \sum_{k=0}^{4} \eta_k \lambda^k$$

(3)

where the coefficients $\eta_i$ have a numerical values corresponding to characteristic of used WECS. The order polynomial is taken equal to $n = 4$. Since $\lambda$ involves a relation between the rotor speed and the wind speed, it is clear that for a certain wind speed, there is a rotor speed at which the maximum power point is reached.

The mechanical dynamic of the WECS can be described by the following set of equations [15-16].

$$J_m \ddot{\omega}_m + B_m \omega_m = T_m - T$$
$$J_e \dot{\omega}_e + B_e \omega_e = T_p - T_e$$

$$T_p \omega_e = T_m \omega_m$$

(4)

where $J_e$ is the total inertia of DC generator, $B_e$ is the coefficient of viscous friction. $T_e$ is the electromagnetic torque. $T_m$ is the rotor torque at the turbine, $J_m$ is the moment of inertia, $B_m$ is the frictional constant of turbine and $\omega_e$ is the angular velocity of the DC-Generator rotor. Note that no torsion related losses are considered here. Furthermore, the transmission is assumed ideal. The transmission gear ratio is defined as

$$\gamma = \frac{\omega_e}{\omega_m}$$

(5)

Using (4)-(5) we get the mechanical equation of the WECS:

$$J \ddot{\omega}_m + B \omega_m = \frac{P_w}{\omega_m} - \frac{P_e}{\omega_m}$$

(6)

where

$$J = J_m + \gamma^2 J_e$$
$$B = B_m + \gamma^2 B_e$$

(7)

In above equations, $J$ denotes the scaled sum of the rotor and generator inertias and $B$ the scaled sum of rotor and generator coefficient of viscous friction. Finally, the WECS model is obtained by combining the dynamics of the DC generator with that of the turbine and is given by:

$$\frac{dI_a}{dt} = \frac{1}{2} \frac{cp(\lambda) \rho R^2 \omega_m^3}{f_{om}} - \gamma \frac{k_e I_a}{f} - \frac{B \omega_m}{f}$$

(8)

where $L_a$ and $R_a$ are respectively the stator winding inductance and resistance. $k_e$ is the induced emf constant, $I_f$ the field current and $v_a$ armature winding voltage.
Let us introduce the state variables $x_1 = \omega_m$ and $x_2 = i_a$. Then (8) yields the following state space representation of the combination ‘turbine – DC Generator’:

$$
\begin{align*}
\frac{dx_1}{dt} &= \frac{1}{2} c p(\lambda) p n R^2 \omega_{win}^2 - \gamma \frac{k_e x_2}{j} - \frac{B x_1}{j} \\
\frac{dx_2}{dt} &= \gamma \frac{k_{el} f x_1}{l_a} - \frac{k_a x_2}{l_a} - \frac{R_a}{l_a}
\end{align*}
$$

(9)

Applying well known averaging technique [3-4], one obtains the following average model for the Boost DC-DC converter as shown in Figure 1:

$$
\begin{align*}
\frac{dx_3}{dt} &= -\frac{1}{c} x_3 + \frac{1}{c} x_2 \\
\frac{dx_4}{dt} &= -(1 - \mu) \left[\frac{R_b x_4 + E_b}{L}\right] + \frac{1}{L} x_3
\end{align*}
$$

(10)

where $x_3$ and $x_4$ denote respectively the (average) voltage $v_a$ and current input $i_L$; $\mu$ is the average value (over cutting periods) of the binary control. Recall that the continuous signal $\mu$, usually called duty ratio, stands as the control input of the system. The objective is to achieve the MPPT requirement by acting on the duty ratio. The state equations obtained up to now constitute a state- space representation of the whole system including the WECS combined with the DC-DC converter and the battery:

$$
\begin{align*}
\dot{x}_1 &= a_1 c p(\lambda) \lambda^{-1} \omega_{win}^2 - a_2 x_1 - a_3 x_2 \\
\dot{x}_2 &= a_4 x_4 - a_5 x_2 - a_6 x_3 \\
\dot{x}_3 &= -a_7 x_4 + a_7 x_2 \\
\dot{x}_4 &= -(1 - \mu) \left[\frac{R_b x_4 + E_b}{L}\right] + \frac{1}{L} x_3
\end{align*}
$$

(11)

where

$$
\begin{align*}
a_1 &= \frac{2 \pi n R^2}{2 j}, a_2 = \frac{b}{j}, a_3 = \gamma \frac{k_e}{j}, a_4 = \gamma \frac{k_{el} f}{l_a}, a_5 = \frac{R_a}{l_a}, a_6 = \frac{1}{l_a}, a_7 = \frac{1}{c}
\end{align*}
$$

3. CONTROLLER DESIGN AND STABILITY ANALYSIS

To facilitate the control development process, the following assumptions are considered:

A1) all the system parameters are known and constants.

A2) all states-space $x_i (i \in \{1, 5\})$ and the wind speed $\omega_{win}(t)$ are measurable.

A2) the wind speed $\omega_{win}(t)$ is constant or slowly time varying (i.e $\dot{\omega}_{win}(t) \equiv 0$)

The control objective is to enforce the speed $\omega_m$ of the wind turbine to track its reference trajectory, $\omega_{m_{ref}} = R^{-1} \lambda_{opt} \omega_{win}$. The maximum power point is reached when $\omega_m = \omega_{m_{ref}}$. Following the backstepping technique [19-21] the controller is designed in four steps:

Step 1. Let us introduce the speed tracking error:

$$
\dot{z}_1 = x_1 - \omega_{m_{ref}}^2 = x_1 - x_1^* \tag{12}
$$

In view of (3) and (11) the above error undergoes the (13):

$$
\dot{\dot{z}}_1 = a_1 \sum_{k=0}^{5} \eta_k \lambda^{k-1} \omega_{win}^2 - a_2 x_1 - a_3 x_2 - x_1^* \tag{13}
$$

In (13) the quantity $\alpha = -a_2 x_2$ stands up as a (virtual) control input for the $z_1$-dynamics. Let $\alpha^*$ denote the stabilizing function (yet to be determined) associated to $\alpha$. It is easily seen from (13) that if $\alpha = \alpha^*$ with:

$$
\alpha^* = -c_1 z_1 - a_1 \sum_{k=0}^{5} \eta_k \lambda^{k-1} \omega_{win}^2 + a_3 x_1 + x_1^* \tag{14}
$$

Then one would get $\dot{z}_1 = -c_1 \dot{z}_1$ with $c_1 > 0$ is a design parameter. This would clearly ensure asymptotic stability of (13) with respect the Lyapunov function:

$$
V_1 = 0.5 z_1^2 \tag{15}
$$

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In effect, the time-derivative of $V_1$ would then be:

$$\dot{V}_1 = z_1 \dot{z}_1 - c_1 z_1^2 < 0$$

(16)

As $\alpha = -a_2 z_2$, is just a virtual control input, one can not set $\alpha = \alpha^*$. Nevertheless, the above expression of $\alpha^*$ retained as a first stabilization function and a new error is introduced:

$$z_2 = \alpha - \alpha^*$$

(17)

Using (14)-(17), it follows from (13) that the $z_1$-dynamics undergoes the (18):

$$\dot{z}_1 = -c_1 z_1 + z_2$$

(18)

Step 2. The objective now is to enforce the error variable to vanish.\((z_1, z_2)\). To this end, let us first determine the dynamics of $\dot{z}_2$:

$$\dot{z}_2 = -a_2 \dot{z}_2 - \dot{\alpha}^*$$

(19)

Based on the assumption A2; (19) together with (11) and (14) implies:

$$\dot{z}_2 = -c_1 z_1 - a_1 \sum_{k=0}^{5}(k-1)\eta_k \lambda^{k-2} \dot{\lambda} \omega_{win}^2 + a_2 x_1 - a_2(a_4 x_1 - a_5 x_2 - a_6 x_3)$$

(20)

where in view of (5)

$$\dot{\lambda} = \frac{\dot{\alpha}_1}{\omega_{win}}$$

(21)

The quantity $\alpha_2 = a_2 a_6 x_3$ lands as virtual control in (20), let $\alpha^*_2$ denotes the corresponding stabilizing function associated to $\alpha_2$, it is clear that if $\alpha_2 = \alpha^*_2$ with:

$$\alpha^*_2 = -c_2 z_2 - z_1 - a_1 \sum_{k=0}^{5}(k-1)\eta_k \lambda^{k-2} \dot{\lambda} \omega_{win}^2 + (a_2 a_4 - a_2) x_1 - a_2 a_5 x_2$$

(22)

Then one would get $\dot{z}_2 = -c_2 z_2 - z_1$ with $c_2 > 0$ is a design parameter. This would clearly ensure asymptotic stability of $(\dot{z}_1, \dot{z}_2)$ errors with respect the Lyapunov function:

$$V_2 = 0.5 z_1^2 + 0.5 z_2^2$$

(23)

As $\alpha_2 = a_2 a_6 x_3$ is just a virtual control input, one can not set $\alpha_2 = \alpha^*_2$. Nevertheless, the above expression of $\alpha^*_2$ retained as a first stabilization function and the thired error is introduced:

$$z_3 = a_2 a_6 x_3 - \alpha^*_2$$

(24)

Using (22)-(24), it follows from (20) that the $z_2$-dynamics undergoes the (25):

$$\dot{z}_2 = -c_2 z_2 - z_1 + z_3$$

(25)

Step 3. Let us investigate the behavior of the error $z_3$, in view of (24), time derivative of $z_3$ gives:

$$\dot{z}_3 = a_2 a_6 \dot{x}_3 - \dot{\alpha}^*_2$$

(26)

From (22) it is readily seen that

$$\dot{\alpha}^*_2 = -c_2 \dot{z}_2 - z_1 + a_2 a_4 \dot{x}_1 - a_2 a_5 \dot{x}_2 - a_2 \dot{x}_1 - a_1 \sum_{k=0}^{5}(k-1)\eta_k \lambda^{k-2} \left( (k-2) \dot{\lambda} (\lambda^{k-3}) \lambda + \dot{\lambda} \right) \omega_{win}^2$$

(27)

Using (11) and (22) it follows from (26) that:

$$\dot{z}_3 = a_2 a_6 (a_2 a_4 - a_2) \dot{x}_1 + a_2 a_5 \dot{x}_2 + a_1 \sum_{k=0}^{5}(k-1)\eta_k \lambda^{k-2}$$
\[
\left( (k-2)\lambda^{(k-3)} \hat{\lambda} + \lambda \right) \omega_{\text{win}}^2
\]  

(28)

In (28), the following quantity \( a_3 = -a_2 a_4 a_3 x_4 \) acts as virtual control. To determine a correspondent stabilizing function \( a_3^* \), let us consider the quadratic augmented Lyapunov function candidate:

\[
V_3 = 0.5z_1^2 + 0.5z_2^2 + 0.5z_3^2
\] 

(29)

Time-derivative of \( V_3 \) along the trajectory of the system \((z_1, z_2, z_3)\) is given by:

\[
\dot{V}_3 = -c_1 z_1^2 - c_2 z_2^2 + z_2 z_3 + z_3 \dot{z}_3
\] 

(30)

The above expression of \( \dot{V}_3 \) suggest the following stabilizing function

\[
a_3^* = -c_3 z_3 - a_2 a_4 a_3 x_2 - c_2 \dot{z}_2 - \dot{z}_1 + (a_2 a_4 - a_2) \dot{x}_1 - a_2 a_5 \dot{x}_2 - z_2 - a_1 \sum_{k=0}^{5} (k-1) k \lambda^{(k-2)} \left((k-2)\lambda^{(k-3)} \hat{\lambda} + \hat{\lambda} \right) \omega_{\text{win}}^2
\] 

(31)

where \( c_3 > 0 \) is a new parameter design. Let us introduce the following error

\[
z_4 = a_3 - a_3^*
\] 

(32)

Combining (31) and (32) yields

\[
\dot{z}_3 = -c_3 z_3 - z_2 + z_4
\] 

(33)

**Step 4.** The objective now is to enforce the error variables \((z_1, z_2, z_3, z_4)\) to vanish, to this end, let us determine the dynamics of \( z_4 \). Deriving (32) and using (11) one obtains:

\[
\dot{z}_4 = a_2 a_4 a_7 \left( (1 - \mu) \frac{[R_0 x_4 + E_{\text{in}}]}{L_c} + \frac{1}{L_c} x_3 \right) - \dot{a}_3^*
\] 

(34)

with

\[
\dot{a}_3^* = -c_3 \dot{z}_3 - a_2 a_4 a_7 \dot{x}_2 - c_2 \dot{z}_2 - \dot{z}_1 + (a_2 a_4 - a_2) \ddot{x}_1 - a_2 a_5 \ddot{x}_2 - \dot{z}_2 - a_1 \sum_{k=0}^{5} (k-1) (k-2) \lambda^{(k-2)} \left((k-3)\lambda^{(k-3)} \hat{\lambda} + \hat{\lambda} \right) \omega_{\text{win}}^2
\] 

(35)

In (35), the actual control input namely \( \mu \) arises for the first time; we seek the stabilization of the full error system \((z_1, z_2, z_3, z_4)\) with respect to the following augmented lyapunov function candidate:

\[
V_4 = V_3 + 0.5z_4^2
\] 

(36)

It is easily checked that, the time derivative of \( V_4 \) is given by:

\[
\dot{V}_4 = -c_1 z_1^2 - c_2 z_2^2 - c_4 z_4^2 + z_3 \dot{z}_3 + z_4 \dot{z}_4
\] 

(37)

It is easily checked that the above derivative suggests the following backstepping control law

\[
\mu = 1 - \frac{1}{a_2 a_4 a_7} \left( \frac{L_c}{[E_{\text{in}} + R_0 x_4]} + \frac{1}{L_c} \right)
\] 

(38)

where \( c_4 > 0 \) is a new design parameter; that is (37) becomes:

\[
\dot{V}_4 = -\sum_{k=1}^{4} c_k \dot{z}_k^2 < 0
\] 

(39)

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The results obtained up to now are summarized in the following theorem.

**Theorem** (Main results). Consider the system of fig.1 and described by the model (11) in close loop with the backstepping controller (38); then one has the following properties:
1. all signals are bounded and the tracking errors \((z_1, z_2, z_3, z_4)\) vanish asymptotically
2. the maximization of the energy captured is achieved.

**Proof.** the \((z_1, z_2, z_3, z_4)\) error-system is given the compact form

\[
\begin{bmatrix}
z_1 \\
z_2 \\
z_3 \\
z_4
\end{bmatrix} =
\begin{bmatrix}
-c_1 & 1 & 0 & 0 \\
-1-c_2 & 1 & 0 \\
0 & -1-c_3 & 1 \\
0 & 0 & -1-c_4
\end{bmatrix}
\begin{bmatrix}
z_1 \\
z_2 \\
z_3 \\
z_4
\end{bmatrix}
\tag{40}
\]

it is readily seen from (39) that

\[
\dot{V} \leq -\rho_1\|[z_1, z_2, z_3, z_4]\|^2
\tag{41}
\]

with

\[
\rho_1 = \min\{c_1, c_2, c_3, c_4\}
\tag{42}
\]

where \(\|\|\) denotes the Euclidian norm, these ensure that the equilibrium \((z_1, z_2, z_3, z_4) = (0,0,0,0)\) of the system (11) is globally exponentially stable [20]. The latter ensure the MPPT objective.

4. **PERFORMANCES EVALUATION**

The performances of the proposed control design are illustrated through simulations. The experimental setup, has been simulated in Matlab/Simulink environment. The involved elements have the following characteristics as shown in Table 1:

| Battery | E_b=24V; R_b=0.65Ω |
| DC-DC converters | L_c=1mH; C=4.7mF |
| DC generator | L_a=11mH; R_a=1.2Ω; J_e=0.208kgm²; J_m=0.011kgm²; Ke=0.353; If=0.15A |
| Air density | \(\rho=1.25\) |
| Wind turbine | J_e=0.1kgm²; J_m=0.015kgm²; R=0.5m; \(\lambda_{opt}=6\) |
| Transmission gear ratio | \(\gamma=11.5\) |

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The values of \(\eta_k(k=0..4)\) in (3) are:

\[
\eta_0 = 121 \times 10^{-4}; \eta_1 = -302 \times 10^{-4}; \eta_2 = 196 \times 10^{-4}; \eta_3 = -34 \times 10^{-4}; \eta_4 = 2 \times 10^{-4}
\]

The controller performances will be evaluated in presence of (time-varying) wind velocity. The wind speed reference as shown in Figure 3 takes a low, medium and high value (equal to 8, 10.7, 14.6 and step to 12.5m/s at times 0, 200, 400 and 500s respectively). With these values of wind speeds, block optimization generates the optimal rotor speed reference shown in Figure 3. The indicated values of design parameters \(c_1 = 75; c_2 = 20; c_3 = 18\) and \(c_4 = 15\) have been selected using a try-and-error search method and proved to be suitable. The controller performances are illustrated by Figure 3 and Figure 4; they show that the machine speed perfectly converge to its reference. The tracking quality is quite satisfactory as the response time (after each change in the wind speed) is less than 10s. The perfect MPPT in presence of wind speed changes is shown in Figure 4. The speed ratio \(\lambda\) converges to its optimal value \(\lambda_{opt} = 8.07\) for which the power coefficient \(C_p(\lambda_{opt}) = 0.407\).
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5. CONCLUSION

In this paper, a new solution to MPPT of variable speed small wind battery-charger system is developed. MPPT is achieved using the nonlinear backstepping controller (38) based on the system nonlinear model (11). The controller is proven to yield a globally uniformly bounded stable closed-loop system via lyapunov-based analysis. Simulation results demonstrate the satisfactory performance of the proposed controller.

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