Nonlinear control of WECS based on PMSG for optimal power extraction

Mohamed Makhad¹, Malika Zazi², Azeddine Loulijat³
¹,²Department of Electrical Engineering, Mohamed V University, Morocco
³Faculty of Sciences and Technology, Hassan First University, Morocco

ABSTRACT

This paper proposes a robust control strategy for optimizing the maximum power captured in Wind Energy Conversion Systems (WECS) based on permanent magnet synchronous generators (PMSG), which is integrated into the grid. In order to achieve the maximum power point (MPPT) the machine side converter regulates the rotational speed of the PMSG to track the optimal speed. To evaluate the performance and effectiveness of the proposed controller, a comparative study between the IBC control and the vector control based on PI controller was carried out through computer simulation. This analysis consists of two case studies including stochastic variation in wind speed and step change in wind speed.

Keywords: Integral backstepping control
          MPPT
          PMSG
          WECS

1. INTRODUCTION

Recently, sustainable energy sources recognized as competitive sources of electrical energy. Despite all these benefits, wind energy is highly intermittent and unpredictable. Therefore, the production of electrical power should not be based exclusively on the wind energy sources, as they are not reliable [1, 2]. Due to these significant advantages in the generation of electrical power, Variable Speed Wind Turbine (VSWT) have been the most extensively installed [3]. Among the generators installed in wind generation systems, the Doubly Fed Induction Generator (DFIG) has an attractive features [3]. The main advantages of the DFIG are: High fault tolerance, low switching loss in rotor-side converters, small size and low cost of converters as compared to the one used in the PMSG [4].

To extract the maximum power, the wind turbine power coefficient should be maintained at its maximum value despite wind variations. This method is carried out using an algorithm called MPPT which delivers the optimal rotational speed [5, 6]. Therefore, to place the system at the point of maximum power, the machine side converter (MSC) control strategy should be effective and robust under real operating conditions. In the literature, Vector control (VC) based on conventional PI correctors is the most popular strategy implemented in many industrial applications [7]. The performances of the PI controller are poor, because the PMSG-based WECS is a variable structure system, while the PI controller is a linear controller which is adjusted for a specific system operating point, so accurate information about system parameters and charging conditions is necessary to ensure good performances [8].

To overcome these drawbacks, many nonlinear control strategies have been successfully designed to extract the maximum energy from the WECS based on PMSG and optimize integration into the electrical distribution grid, such as Fuzzy Logic Control [9], Feedback Linearization technique [10], SMC [8].
In [11], to reduce hardware complexity, the authors have developed a Modified Particle Swarm Optimization (MPSO) Backpropagation Learning Algorithm to adjust PI parameters with sensorless control of a PMSG to achieve high performances in MPPT operation. The MPSO is also used by is [12] to optimise the MPPT algorithm in a Wind-Tidal Hybrid. In [13], the authors designed a robust nonlinear predictive control (RNPC) to regulate the reference voltages and stator currents of the PWM rectifier in presence of matched uncertainties and external disturbances, with validation via implementation on a dSPACE hardware. In [14], the authors developed a higher order SMC controller with hardware implementation, for a variable speed wind turbine based on PMSG integrated to an infinite power grid. Moreover, the Backstepping approach it is one of the most a nonlinear controllers suggested for the VSWT [15].

The main objective of the MSC control is to place the operating point of the WECS at the maximum power point (MPP). To achieve this goal, the control regulates the rotational speed of PMSG to track the optimal speed. For the GSC converter control, the purposes are: regulation of the DC bus voltage and to ensure a connection to the electrical network with a unit power factor (UPF). This paper is organized as follows: Section 2 presents the mathematical model of the system composed of the wind turbine and the PMSG. In the third section the proposed IBC control strategy for maximizing the extracted power is designed. The simulation results are presented and compared in section four. Finally, in the last section a brief conclusion is included. Figure 1 illustrates the configuration of a PMSG-based wind energy conversion system connected to the power grid.

![Figure 1. Configuration of WECS based on PMSG](image)

2. MATHEMATICAL MODEL OF WIND TURBINE

In this section the mathematical simplified turbine model is proposed. The expression of the mechanical power $P_T$ extracted from the wind and the tip-speed ratio $\lambda$ are given by:

\[
\begin{align*}
P_T &= \frac{1}{2} C_p(\lambda, \beta) \rho \omega \pi R^2 V^3 \\
\lambda &= \frac{R \omega}{V}
\end{align*}
\]

(1)

where: $V$ the wind speed (m/s), $\rho$ is the air density, $R$ is the rotor blade radius, $C_p(\lambda, \beta)$ is the power coefficient and $\omega$ is the rotational speed (rad/s). Based on the turbine characteristics, a generic equation employed to describe the power coefficient $C_p(\lambda, \beta)$ can be expressed as follows [16]:

\[
C_p(\lambda, \beta) = 0.22 \left( \frac{116}{\lambda_i} - 0.4, \beta - 5 \right) e^{-12.5 \beta / \lambda} ; \quad \frac{1}{\lambda_i} = \frac{1}{\lambda + 0.089 \beta} - \frac{0.035}{\beta^2 + 1}
\]

(2)
The variation of the coefficient $C_p(\lambda, \beta)$ as a function of tip speed ratio for various values of the pitch angle $\beta$ is given in the Figure 2(a), while Figure 2(b) presents the curves of the mechanical power $P_m$ in function of rotational speed $\omega_m$ for various wind speed. As illustrated in Figure 2(b), the WECS operation consists of four zones. Zone 1 and 4 corresponding to the shut-down of the wind turbine when the wind speed is below and exceeds the limits of the speed operating range, respectively. In zone 2 the wind turbine operates in MPPT mode, in order to extract the maximum power available. Zone 3 corresponds to constant power mode operation through the activation of the pitch angle controller. The characteristics in Figure 2(b) show that the maximum power coefficient $C_p = 0.43$ is obtained for $\lambda_{opt} = 6.42$ and pitch angle $\beta = 0$.

![Figure 2. (a) Characteristics $C_p(\lambda, \beta)$ for various values of the pitch angle $\beta$, (b) Mechanical power curves at various wind speed](image)

3. DYNAMIC MODEL OF PMSG

The mathematical model of the PMSG in in the synchronous frame (d-q) is described by the following equations [17, 18]:

\[
\begin{align*}
\dot{i}_d &= -\frac{R_s}{L_d} i_d + \omega \frac{L_{sd}}{L_d} i_q + \frac{v_{sd}}{L_d} \\
\dot{i}_q &= -\frac{R_s}{L_q} i_q - \omega \frac{L_{sq}}{L_q} i_d - \omega \frac{\psi_f}{L_q} + \frac{v_{sq}}{L_q} \\
T_e &= \frac{3}{2} p \psi_f i_q \\
\dot{\omega}_m &= \frac{T_e}{J} - f \frac{\omega_m}{J} - \frac{T_m}{J}
\end{align*}
\]

where: $v_{sd}, v_{sq}$ are stator voltage components in d-q reference frame. $i_{sd}, i_{sq}$ are stator current components in d-q reference frame. $\psi_f$ is permanent flux linkage. $R_s$ is the stator resistance. $\omega$ is the electrical speed (rad/s), $p$ is number of pole pairs. $L_{sd}$ and $L_{sq}$ are stator inductance components in d-q reference frame. $T_e$ is the electromagnetic torque of the PMSG. $J$ is the total moment of inertia. $f$ is the viscous friction coefficient. $T_m$ is the mechanical torque developed by the wind turbine. $\omega_m$ is the rotational speed of the PMSG.

4. INTEGRAL BACKSTEPPING CONTROL DESIGN

In this section the The Integral backstepping controllers is designed for control the MSC in WECS based on PMSG. The IBC control based on the decomposition of the system into subsystems in descending order, while checking the stability of each subsystem in the sense of Lyapunov, which gives it the qualities of robustness and overall asymptotic stability [19-21]. The Backstepping approach involves the recursive selection of certain functions of state variables as virtual control inputs for dimensional subsystems [22-25].
4.1. Design of rotational speed controller

For dynamics (4), the speed error $e_m$ is defined as follows:

$$ e_m(t) = \omega_m^* - \omega_m + \kappa_1 \int (\omega_m^* - \omega_m) \, dt $$

(5)

where $\kappa_1$ is constant of integral action.

Theorem 1: the following virtual control ensures the asymptotic convergence of the dynamics (4):

$$ i_{sv}^* = \frac{2J}{3 \psi_f} \left( \kappa_m e_m + \omega_m^* + \frac{f}{J} \omega_m + \frac{T}{J} + \kappa_1 (\omega_m^* - \omega_m) \right) $$

(6)

where $\kappa_m$ is a positive control gain that depends on the MSC features.

Proof: to prove that $\omega_m$ tracks the optimal speed $\omega_m^*$, consider the Lyapunov function $V_1$ definite by:

$$ V_1 = 0.5 e_m^2 $$

(7)

the derivative of $V_1$ along the trajectory is given by:

$$ \dot{V}_1 = e_m \dot{e}_m = e_m \left( \omega_m^* + \frac{3}{2} \frac{J}{\psi_f} i_{sv}^* + \frac{f}{J} \omega_m + \frac{T}{J} + \kappa_1 (\omega_m^* - \omega_m) \right) $$

(8)

substituting (6) in (8), we prove that:

$$ \dot{V}_1 = - \kappa_m e_m^2 \leq 0 $$

(9)

based on the inequality (9), the asymptotic stability of the subsystem (4) is guaranteed if the gain $\kappa_m$ is positive. This completes the proof.

4.2. Currents controller design

To ensure that $i_{sq}$ tracks the current $i_{sq}^*$, the current error is defined as follows:

$$ e_q(t) = i_{sq}^* - i_{sq} + \beta_1 \int (i_{sq}^* - i_{sq}) \, dt = i_{sq}^* - i_{sq} + e_q $$

(10)

where $\beta_1$ is constant of integral action.

Theorem 2: the following voltage control $v_{sq}^*$ ensure that $i_{sq}$ tracks the current $i_{sq}^*$:

$$ v_{sq}^* = L_{sq} \left( \beta_q e_q + \frac{R_q}{L_{sq}} i_{sq} + \omega_m \frac{L_{sd}}{L_{sq}} i_{sd} + \frac{\psi_f}{L_{sq}} \right) $$

(11)

where $\beta_q$ is a positive control gain, chosen according to the requirements imposed by the MSC.

Proof: to confirm that the trajectory of the subsystem (3.a) converge to the current reference. Consider a second Lyapunov function chosen as follows:

$$ V_2 = V_1 + 0.5 e_q^2 + 0.5 e_q^2 $$

(12)

the time derivative of $V_2$ is given by:

$$ \dot{V}_2 = - \kappa_m e_m^2 + e_q \dot{e}_q + \dot{e}_q e_q = - \kappa_m e_m^2 + e_q \left( i_{sq}^* - i_{sq} + e_q \right) + e_q \dot{e}_q $$

(13)

after simplification the expression (13) becomes:

$$ \dot{V}_2 = - \kappa_m e_m^2 - (\beta_q - \beta_1) e_q^2 - \beta_1 e_q^2 \text{ if } \beta_q \geq \beta_1 \text{ then } \dot{V}_2 \leq 0 $$

(14)

in order for the closed loop (3.a) to be asymptotically stable, the condition $\beta_q \geq \beta_1$ must be verified. This completes the proof.
In this second step to regulate the d-axis current, the d-axis error $e_d$ is defined by:

$$e_d(t) = i_{sd}^* - i_{sd} + \alpha_1 \int (i_{sd}^* - i_{sd}) dt = i_{sd}^* - i_{sd} + e_d^*$$  (15)

where: $\alpha_1$ is a positive control gain, the value is dependent on the MSC features.

Theorem 3: the following voltage control $v_{sd}^*$ assures the asymptotical convergence to zero of the d-axis error:

$$v_{sd}^* = L_{sd} \left( \alpha_d e_d^* + \frac{R_s}{L_{sd}} i_{sd} - \omega_s \frac{L_{sq}}{L_{sd}} i_{sq} \right)$$  (16)

where: $\alpha_d$ is a positive parameter chosen according to the requirements imposed by the MSC.

Proof: to check the stability of subsystem (3.b), a third candidate function Lyapunov $V_3$ is defined as follows:

$$V_3 = 0.5 e_d^2 + 0.5 \dot{e}_d^2$$  (17)

deriving $V_3$ with respect to time we obtain:

$$\dot{V}_3 = -\alpha_d e_d^2 + \alpha_1 \left( e_d^2 - \dot{e}_d^2 \right) = -\left( \alpha_d - \alpha_1 \right) e_d^2 - \alpha_1 \dot{e}_d^2$$  (18)

finally, if $\alpha_d \geq \alpha_1$ then $\dot{V}_3 \leq 0$, as a result the dynamic (3.b) is asymptotically stable. This completes the proof.

5. SIMULATION RESULTS AND DISCUSSIONS

This section presents the simulation results of the WECS based on a 2MW PMSG. The PMSG-based WECS presented in Figure 1 was simulated in Matlab/Simulink environment. In addition, the PMSG parameters and the controller gains are given in Tables 1 and 2, respectively. The performance and feasibility of the IBC control are compared to that of PI corrector under four cases, stochastic wind speed variation and step change of wind speed. The IBC control strategy scheme is presented in Figure 3.

![Figure 3. Block diagram of the IBC controller](image-url)
5.1. Operation under stochastic wind speed variation

In this case a stochastic wind speed profile is simulated to investigate the performance of the proposed controllers in response to a more realistic wind speed. The wind speed varies between 8 m/s and 12 m/s, exceeding the rated speed from the instant t=5.8s to t=7s. The simulation results are presented in Figure 4 and Figure 5. For greater visibility, the simulation results are presented irrespective of the ripples generated by Pulse Width Modulation (PWM). As shown in Figure 4(a), the pitch angle is set to zero in MPPT operation. From t=5.8s to 7s, the wind speed exceeds v=12m/s. In this particular situation, the pitch angle controller is enabled, hence the angle \( \beta \) is adjusted in the range 0° to 4° in order to limit the output power of the PMSG. According to Figure 4(b) at variable speed the IBC controller is able to track the optimal speed with higher precision as compared to PI controller.

Table 1. Parameters of the WECS based on PMSG [18]

| PMSG parameters     | Values  | Wind turbine parameters | Values |
|---------------------|---------|-------------------------|--------|
| \( P_r \) rated power | 2 MW    | \( \rho \) the air density | 1.08 kg/m³ |
| \( \omega_m \) mechanical speed | 2.57 rad/s | \( V \) base wind speed | 12 m/s |
| \( R \) stator resistor | 0.008 Ω | \( C_{p_{max}} \) optimal power coefficient | 37 m |
| d-axis and q-axis inductance | 0.0003 H | \( R_b \) blade radius | 0.43 |
| \( \Psi_f \) Permanent flux | 3.86 Wb | \( \lambda_{opt} \) Optimal tip speed ratio | 673 |
| \( P \) pole pairs | 60      |                         |        |

Table 2. IBC control gains

| \( k_m \) | 0.001 | \( \beta_1 \) | 5000 | \( \alpha_1 \) | 5000 |
|-----------|-------|---------------|------|---------------|------|
| \( k_1 \) | 60    | \( \beta_1 \) | 70   | \( \alpha_1 \) | 70   |

Figure 4. (a) Wind speed profile and pitch angle, (b) PMSG speed, (c) Generator torque, (d) PMSG active power.
Figure 4(c) and Figure 4(d) indicate that the IBC control provides good performance at variable speed in terms of extracting the maximum power compared to that obtained with the PI controller. While, in the range \( t=5.8s \) to 7s, it can be seen that the torque and power are limited to the rated values by the pitch angle control. As mentioned in Table 3, it is obvious that the current and DC bus voltage ripples are very high under the IBC control compared to the PI corrector. Finally, Figure 5(b) presents the measurement of the total harmonic distortion (THD) of stator currents at moments \( t=2s, t=5s \) and \( t=10s \). From these data, we can remark that the THD under IBC controller is slightly higher than those obtained with PI control. Noting that the high frequency ripples produced by the IBC controller due to the nonlinear aspect of this approach.

| Table 3. Performance achieved by the two controllers |
|---------------------------------------------------|
| \( U_{DC} \) ripple | ±2.8V | 3V |
| \( I_d \) ripple | ±0.02 pu | ±0.015 pu |
| \( I_q \) ripple | ±0.004 pu | ±0.0095% |
| Max tracking error | ±4% | ±0.45% |

Figure 5. (a) PMSG stator currents \( I_{abc} \), (b) Total harmonic distortions (THD) of stator currents

5.2. Operation under step change of wind speed

To evaluate the transient and steady state performances obtained by the controllers studied during an abrupt change in wind speed, a series of two consecutive step changes in wind speed are applied as follows: 8 m/s to 10 m/s, 10 to 12 m/s, at \( t=2 \) s and \( t=10 \) s, respectively. The simulation responses are provided in Figure 6 and Figure 7. Figure 6(b) presents the PMSG rotational velocity in response to two consecutive steps of wind speed under the PI and IBC controllers. This figure shows that both regulators have good steady-state performance.

Figure 6. (a) Wind speed profile, (b) PMSG speed (rad/s)
During transient operation, under the two controllers, the speed response time is 0.15s, with a considerable overshoot under the PI corrector. It is important not to forget that the steady-state speed ripples are very high under the IBC control owing to the nonlinear design of the Backstepping control. As illustrated in Figure 7(a), the waveform of the power coefficient under the IBC and PI controllers are identical transient response with a small derivation. In Figure 7(c) and Figure 7(d), the IBC controller provides smoother operation compared to PI controller.

![Figure 7. (a) Power coeffient, (b) Stator currents of the PMSG, (c) PMSG torque, (d) PMSG active power](image)

6. CONCLUSION

A novel Integral Backstepping controller is designed in the paper in order to achieve MPPT of a PMSG based variable speed wind turbine. An evaluation of the performance and effectiveness of the proposed controller is compared with that obtained by the conventional PI corrector through two case studies: step change in wind speed and stochastic change in wind speed. The simulation results show that classical PI-controller has poor performance during transient operation, especially in MPPT operation. The two case studies confirmed that that IBC can rapidly reach the MPPT with the least overshoot under step change in wind speed and stochastic change in wind speed. However, the THD of stator currents indicates that the deformation of the stator currents under the IBC is slightly higher in comparison with the one of PI controller. This THD value is a result of the nonlinear design of the IBC control. Thanks to this comparative analysis, we can say that the robust Integral Backstepping controller is an attractive technique in the control of wind energy conversion systems (WECS) based on PMSG.
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