Robust MPPT Control of PMSG Wind Turbines Using Sliding Mode Control

Driss Gezzaz[1*], *Sabah* Miqoi[2], and *Abdelghani* El Ougli[1]
[1] Computer Science, Signal, Automation and Cognitivism Laboratory, Faculty of Sciences Dhar El Mahraz Fez, Fez, 30050 Morocco
[2] Team of Embedded Systems, Renewable Energy and Artificial Intelligence, National School of Applied Sciences, Mohammed First University Oujda, Oujda, Morocco

Abstract. Wind energy is becoming an increasingly promising technology and a more significant player in energy production. However, due to the nonlinear nature of the system and the impact of external conditions, an effective control strategy is crucial. In this paper, we employ Sliding Mode Control as a Maximum Power Point Tracker (MPPT) on a Buck-Boost converter to connect the DC load to the wind turbine generator. All system components are modeled and simulated using MATLAB/Simulink, and the results demonstrate the promising potential of the SMC method.

1 Introduction

Wind turbines with Permanent Magnet Synchronous Generators (PMSGs) have gained significant attention for their high torque-to-current ratio, large power-to-weight ratio, exceptional efficiency, and robustness. However, these systems face challenges due to their nonlinearity, uncertainties, and disturbances caused by wind variations. To address these issues, a robust nonlinear MPPT controller is essential [2,3].
MPPT algorithms are categorized into conventional methods—such as Tip Speed Ratio (TSR), Optimum Torque (OT), Perturb & Observe (P&O), and Hill Climb Search (HCS)—which often rely on multiple sensors and can be complex. Non-conventional methods, including Fuzzy Logic Control (FLC), Artificial Neural Networks (ANN), and Sliding Mode Control (SMC), offer greater effectiveness, robustness, and simpler implementation [1,4].
This research employs SMC as the MPPT due to its robustness, fast response, and ease of implementation. The system features a PMSG that generates three-phase electrical power, converted to DC power via a three-phase rectifier, and then optimized for maximum power output using a Buck-Boost converter. Simulations conducted in MATLAB/Simulink demonstrate the promising potential of SMC.

2 System modelling

The overall system is shown in figure including the wind turbine, the PMSG, the rectifier and the buck-boost converter.

* Corresponding author: gezzaz.driss@gmail.com

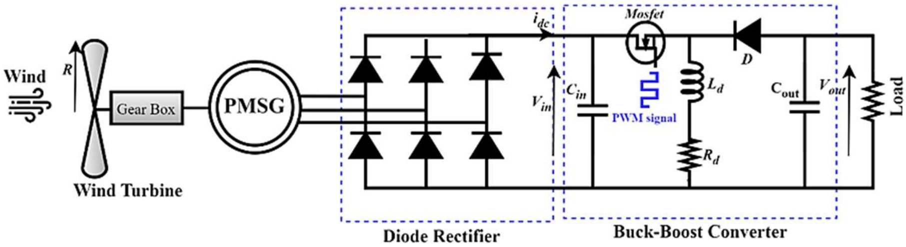

Fig. 1. Wind Turbine System model

2.1 Modelling of the turbine

2.1.1 Aerodynamic model:

The power produced by a moving air mass with a speed of υ across an area A with air density ρ can be articulated as follows [5,6]:

$$P_w = \frac{1}{2}\rho A \vartheta^3 \tag{1}$$

The mechanical power P_m supplied by this turbine to the generator can be expressed as

$$P_m = \frac{1}{2}\rho A \vartheta^3 C_p(\beta,\lambda) \ \ with \ \ \lambda = \frac{\omega R}{\vartheta} \ \ and \ \ C_p = \frac{P_m}{P_w} \tag{2}$$

Where C_p is the power coefficient depending on the pitch angle β and the tip speed ratio λ,ω is the turbine rotor speed and R is the turbine radius.

Several numerical approximations have been developed in the literature to determine an expression for the Cp coefficient. We choose to use the one adopted by MATLAB Library:

$$C_p(\beta,\lambda) = 0{,}5176\left(\frac{116}{\lambda_i} - 0{,}4\beta - 5\right) exp^{-\frac{21}{\lambda_i}} + 0{,}006795\lambda_i \tag{3}$$

$$\lambda_i = \frac{1}{\frac{1}{\lambda+0{,}08} - \frac{0{,}035}{\beta^3+1}} \tag{4}$$

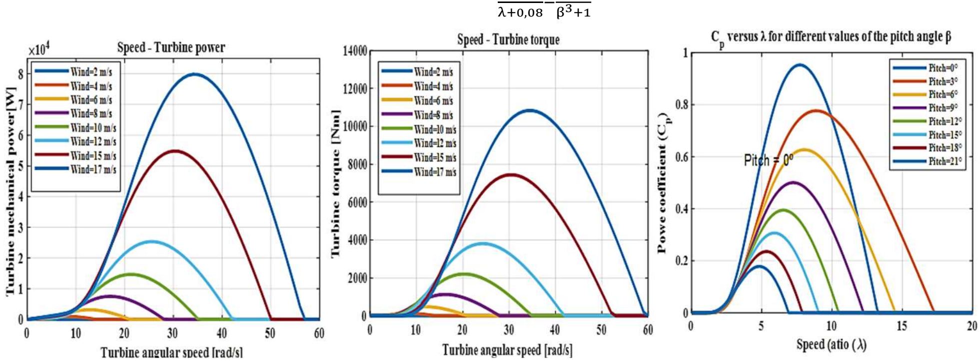

Fig. 2. Wind Turbine characteristics

2.1.2 Mechanic Model

The wind turbine generator drive that represents the mechanical bloc can be given by [5,6]:

$$T_t - T_{em} = J\frac{d\omega}{dt} - f_m\omega \tag{5}$$

With T_{em} is the electromagnetic torque produced by the generator, $T_t = \frac{P_m}{\omega}$the turbine torque, fm the viscous friction coefficient of the machine and J the rotor inertia.

The dynamic model of the PMSG can be simplified by the following equations:

$$\frac{di_d}{dt} = -\frac{R_s}{L_d}i_d + \frac{L_q}{L_d}\omega i_q + \frac{1}{L_d}v_d \tag{6}$$

$$\frac{di_q}{dt} = -\frac{R_s}{L_q}i_q + \frac{L_d}{L_q}\omega i_d - \frac{1}{L_q}\omega\phi_m + \frac{1}{L_q}v_q \tag{7}$$

where d,q are the synchronous rotating reference frame; R_s is the armature resistance; L_d,L_q; i_d,i_q; v_d,v_q are respectively the generator inductance, the currents and voltages of d-q axis, andϕ_m is the permanent magnet flux.

In the *d-q* synchronously rotating reference frame, the electromagnetic torque is represented by:

$$T_{em} = \frac{3}{2}p[(L_d - L_q)i_d i_q + \phi_m i_q] \tag{8}$$

2.2 Buck-boost Converter

The circuit of the buck-boost converter is illustrated in figure 1. The averaged model of the circuit is given by [3]:

$$\frac{di_{L_d}}{dt} = -\frac{R_d}{L_d}i_{L_d} + \frac{V_D+V_{out}+V_{in}}{L_d}u - \frac{V_D+V_{out}}{L_d} \tag{9}$$

$$\frac{dV_{in}}{dt} = \frac{i_{dc}}{C_{in}} - \frac{i_{L_d}}{C_{in}}u \tag{10}$$

Here, D represents the duty cycle, which will be controlled by the MPPT:

$$D = \frac{V_{out}}{V_{out}-V_{in}} \tag{11}$$

$$\frac{d}{dt}\begin{pmatrix}\omega\\ i_d\\ i_q\\ i_{L_d}\\ V_{in}\end{pmatrix} = \begin{pmatrix} f_m & \frac{3}{2j}p(L_d-L_q)i_q & \frac{3}{2j}p\phi_m & 0 & 0\\ \frac{L_q}{L_d} & -\frac{R_s}{L_d} & 0 & 0 & 0\\ \frac{L_d}{L_q}\phi_m & \frac{L_d}{L_q}\omega & -\frac{R_s}{L_q} & 0 & 0\\ 0 & 0 & 0 & -\frac{R_d}{L_d} & 0\\ 0 & 0 & 0 & 0 & 0\end{pmatrix}\begin{pmatrix}\omega\\ i_d\\ i_q\\ i_{L_d}\\ V_{in}\end{pmatrix} + \begin{pmatrix}0\\ 0\\ 0\\ \frac{V_D+V_{out}+V_{in}}{L_d}\\ -\frac{i_{Ld}}{C_{in}}\end{pmatrix}u + \begin{pmatrix}\frac{T_t}{j}\\ \frac{v_d}{L_d}\\ \frac{v_q}{L_q}\\ \frac{-V_D-V_{out}}{L_d}\\ \frac{i_{dc}}{C_{in}}\end{pmatrix} \tag{12}$$

$$\dot{x} = f(x).x + g(x).u + d \tag{13}$$

3 Control strategies

3.1.1 Sliding Mode Control

SMC is a nonlinear control algorithm that maintains system stability by keeping the trajectory on a specific sliding surface. A crucial element of SMC is the design of this sliding surface, S(x). Maximum power is achieved when the ratio of power change to angular speed change is zero (as it is shown in figure 2), is described by the corresponding equation [5,8].

$$S = \frac{dP_m}{d\omega} \tag{14}$$

The controller's structure comprises two components: the first is aimed at stabilization, while the second (the equivalent control) focuses on precise linearization:

$$u(t) = u_n + u_{eq} \tag{15}$$

$u_{eq}(t)$ is determined based on the system behavior along the sliding mode, where $\dot{S}(x,t) = 0$. Hence:

$$u_{eq} = [\frac{\partial S}{\partial x}.g(x,t)]^{-1}[\frac{\partial S}{\partial x}.f(x,t)] \tag{16}$$

The switching signal u_n is determined as:

$$u_n = K.sign(S(x)) \tag{17}$$

Where K is the control gain

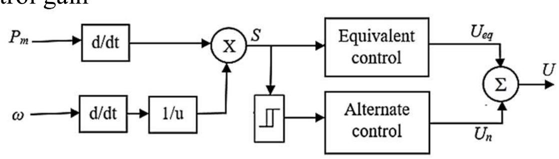

Fig. 3. SMC block diagram

In this control mode, it is essential to verify the Lyapunov condition:

$$S(x).\dot{S}(x) < 0 \tag{18}$$

3.1.2 Perturb & Observe

P&O is used in this paper to evaluate and validate the SMC method. Its principle is illustrated in the figure [7].

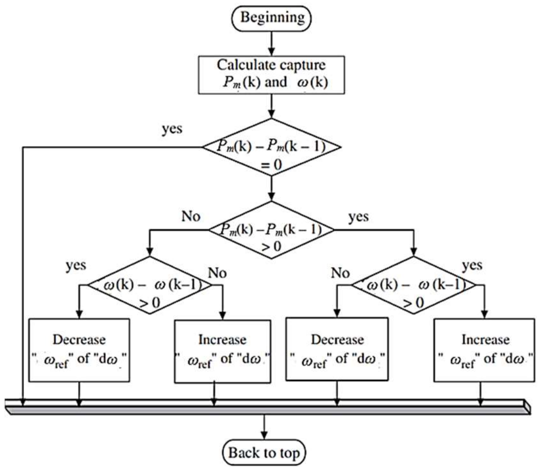

Fig. 4. P&O Control Diagram

4 Simulation results:

To verify the proposed control method for wind energy applications, simulations are conducted using MATLAB/Simulink. The characteristics of the Wind Energy Conversion System (WECS) used in the simulation are detailed in the tables. The test is conducted by varying the wind speed as shown in figure 5.

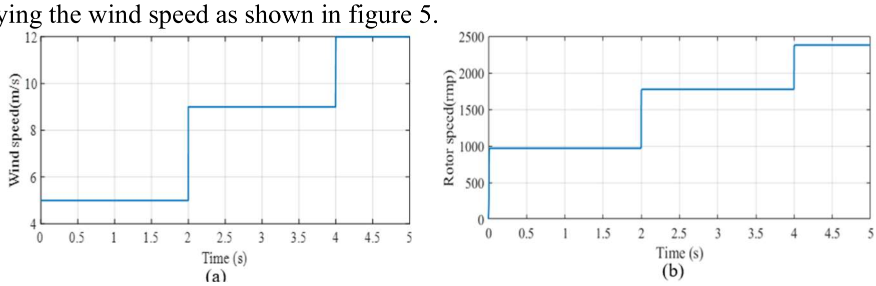

Fig. 5. (a)Wind Speed, (b)Rotor Speed

Figure 6 shows the mechanical power P_m, and the stator current and voltage.

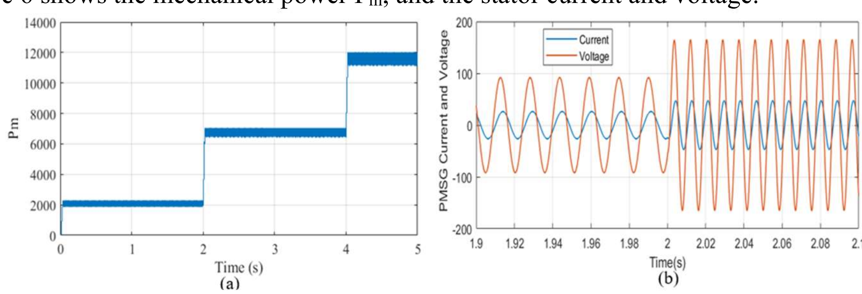

Fig. 6. (a) mechanical power, (b) stator current and voltage

Table 1. System parameters

Parameter	Value	Parameter	Value
P_m (W)	20000	L_d	4µH
$R_s(\Omega)$	0,918	C_{in}	1µF
Armature Conductance	0.97mH	C_{out}	4ηF

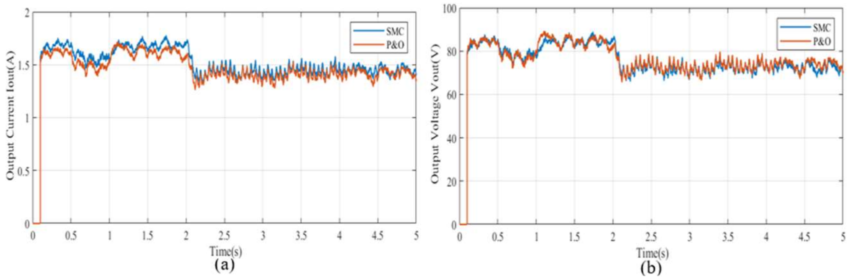

Fig. 7. (a)output current, (b)output voltage

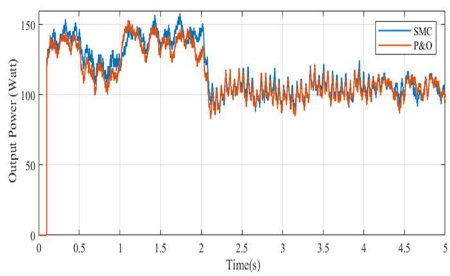

Fig. 8. System output power

Figures 7 and 8 display the output current, voltage, and power, demonstrating that the Sliding Mode Control (SMC) tracks the Maximum Power Point (MPP) with a slight advantage over Perturb & Observe (P&O). Both controllers exhibit some perturbation around the MPP, which in the case of SMC may be due to chattering phenomena.

5 Conclusion

In this paper, a sliding mode controller (SMC) is applied to a PMSG-based wind turbine and compared with a perturb and observe (P&O) controller. Simulation results using MATLAB/Simulink indicate that the SMC method outperforms the P&O controller, though it exhibits oscillations around the maximum power point (MPP).
This issue can be reduced or eliminated by integrating SMC with fuzzy logic, adaptive control, or artificial neural networks (ANN), or by employing a higher-order SMC approach

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