Research Article

Novel Nonlinear Control and Optimization Strategies for Hybrid Renewable Energy Conversion System

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This article deals with a hybrid renewable energy conversion system (HRECS) interconnected to the three-phase grid in association with their power conversion components, i.e., AC/DC rectifier and DC/AC inverter. The HRECS is built around a permanent magnet synchronous wind turbine generator and a photovoltaic energy conversion system. Comparing to traditional control methods, a new multiobjective control strategy is developed to enhance system performances. This makes it possible to account in addition to optimal turbine speed regulation and PV-MPPT and three other important control objectives such as DC-link voltage regulation and the injected reactive power in the grid. To achieve these objectives, a novel control strategy is developed, based on a nonlinear model of the whole “converters-generators” association. The robustness and the stability analysis of the system have been proved using the Lyapunov theory and precisely the backstepping control and the sliding mode control. The performances of the proposed controllers are formally analyzed with respect to standard control solutions illustrated through simulation.

1. Introduction

Today, the use of energy is one of the clearest indicators of country development. The most industrialized and energy-consuming nations continue to rely on energy as a driver of growth and economic development. Its contribution to the creation of national wealth is not limited to its own added value but affects all the other sectors of which it allows the activity. The capital importance of investments in this sector and their life span mean that the strategic choices made today will shape the future energy landscape. In addition, our planet can no longer physically bear the greenhouse emissions that the world has known for the past years. Climate change and the disruption of many ecological balances would cause irreversible damage. We are therefore faced with the need to implement sustainable policies with three components: economic, social, and environmental [1].

Wind and solar power are the most used renewable energy resources [2]. It generates clean and climate-friendly electricity, jobs, and reduces risks on several levels, as exposure to particles and susceptibility to the prices of imported fuels. When comparing different technologies on the basis of the parameters, the cost of wind power decreases significantly compared to the high price of power generation. This is mainly due to the very positive effect on locals.

The hybrid energy conversion system (HECS) makes reference to multisource electrical production [3]. It combines different renewable sources. The main advantage of HECS is that it is self-sufficient in all climatic conditions, because it does not depend on a single source. HECS can be connected to the power grid or operate as a stand-alone microgrid [4, 5].

Many works have been dispersed around these electrical production systems. The authors develop a framework for producing electrical energy from wind based on fixed frequency and fixed speed control systems. The drawbacks of these kinds of systems are well discussed in [6–16], where the authors present a nonlinear controller for a system powered by an AC-DC-AC converter. This method makes the system more...
manageable, which allows the implementation of variable speed control to optimize power extraction and at the same time ensure the requirement of power factor correction (PFC). However, with the advent of power electronics and the increasing availability of semiconductor devices operating at high currents and voltages, variable speed systems are used more and more. In this configuration, the network frequency and the machine rotation speed are decoupled. This speed can therefore vary so as to optimize the aerodynamic efficiency of the wind turbine and dampen the torque fluctuations in the power train. However, it should be emphasized that the optimal choice of the production system was not decided by considering only the generator. The optimal choice is one that minimizes the cost of the energy produced by the wind power plant.

Regarding photovoltaic grids, several structures have been proposed in the literature. For larger plants, a three-phase grid is usually used. In [17–25], the chopper is directly connected to the output of the PV generator and is controlled to maximize the power extracted from the photovoltaic panel and adjust the input voltage direction between the terminals. The utility grid provides the inverter of the input energy. In order to improve this structure, only one inverter can be used between the PV generator and the three-phase grid [26, 27]. This simpler structure avoids the disadvantages of using a chopper (extra losses, investment, and maintenance). In this case, the input voltage at the inverter terminals is not constant but varies according to the maximum power extracted from the photovoltaic panel. With this structure, the inverter is controlled to meet two goals: (i) MPPT requirements and (ii) DC and AC voltage source adaptation.

In addition, MPP varies with irradiance and temperature. If we want to transmit the maximum power, we need to continuously adjust the array terminal voltage. Different technologies for maximizing the transmission of photovoltaic power to various loads are reported in the literature, including constant voltage method, open-circuit voltage method, short circuit method, Perturb and Observe method (P&O), Incremental Conductance method (IncCond), Ripple-Related Control (RCC) method, and Power Optimal Voltage (POV) optimizer. The constant voltage method is the simplest method, but it has been commented that it can only collect about 80% of the maximum power available under different irradiance. In this paper, a new control strategy involves an optimal voltage reference generator and an adaptive sliding mode controller (SMC) in the sense to extract the maximum power from photovoltaic generator regardless of solar radiation.

Now, the focus is made on hybrid energy system (HES) which combines a wind energy conversion system (WECS) and photovoltaic system (PVS) [28, 29]. A good number of recent works deal with such a problem. In [30–32], the authors present an optimization method based on the use of a fuzzy logic controller and PI controller successively for a PV-wind standalone system. These controllers badly considered as robust controllers are mediocly hand-tuned because they do not exploit to a full extent the nonlinear plant characteristic, so their performance is far from being stringent and time optimal. While [24, 33, 34] propose an approach to optimize the sizing of a multisource PV/wind with hybrid energy storage system (HESS), this paper does not deal with a controller study but just an algorithm to manage energy production.

To face all these drawbacks, a novel structure, as shown in Figure 1, is proposed. The aim is to propose a fully novel nonlinear controller applied to a hybrid energy system (HES) based on the combination of wind energy conversion (WEC) system and photovoltaic energy production system (PV). These include permanent magnet synchronous generators (PMSG) that convert wind turbine power into electrical energy. The corresponding voltage output amplitude and frequency vary with the variation of the wind speed. PMS generators have many advantages in wind power applications due to their high-power density, high efficiency (because the copper loss in the rotor disappears), and reduced effective weight. These features make it possible to achieve the high performance of PMSG variable speed control and very loyal operating conditions (reducing maintenance requirements).

To meet MPPT requirements, PMSG is connected to the DC-link across a pulse width modulation-(PWM-) controlled rectifier. The control of the hybrid renewable energy structure (PV/wind) is ensured by two proposed nonlinear controllers, namely, the backstepping control and the sliding mode control which allow the management and optimization of the energy injected into an electrical grid.

A DC-DC converter is used between a PV generator and DC-Bus to achieve an MPPT requirement. To adapt the electric energy to the grid, an IGBT-based inverter (DC/AC PWM converters) (Figure 1) is used.

This paper is organized as follows: the whole system model is presented in Section 2; the state-feedback controller is designed and analyzed in Section 3. Several simulations in MATLAB/SIMULINK based on an accurate system model is made to show the controller performances in Section 4.

2. System Modelling

The controlled HREC system is illustrated by Figure 1. This structure consists of three subsystems: a combination of “synchronous aerogenerator-AC/DC converter,” an association of “photovoltaic panels-DC/DC boost converter,” and DC/AC boost rectifier which is used to achieve the maximum power point tracking (MPPT) and interface the PV array output to the DC-link voltage. All electronic power converters operate according to the known pulse width modulation principle (PWM). To give the flexibility to extract the maximum power from photovoltaic panels and wind turbine, the last both subsystems are coupled through a DC bus via a grid filter.

2.1. The PV Panels-DC/DC Boost Converter Association Modelling

2.1.1. Photovoltaic Generator Model. The direct conversion of solar energy into electrical power is obtained by photovoltaic solar cells. A PV panel consists of connected several numbers of matrix cells. The single photovoltaic cell can be described by the equivalent circuit (Figure 2), where $I_{ph}$ is the photocurrent (generated current under given radiation); $R_s$ and $R_{sh}$ are the resistances that represent the contact resistances [22, 23].
The known \((I_c - V_c)\) characteristics of a solar array are given by the following equation \([22]\):

\[
I_c = I_{ph} - I_{D} - I_{sh} = I_{ph} - I_{s} \exp\left(\frac{qV_D}{nK_BT}\right) - \frac{V_D}{R_{sh}},
\]

where \(I_s\) is the cell reverse saturation current; \(T\) is the cell temperature; \(K_B\) is the Boltzmann constant; \(q\) is the electron charge; and \(n\) is the ideality factor.

Let us apply Kirchhoff’s law; the voltage across the diode writes as

\[
V_D = V_c + R_s I_c.
\]

The PV generator is composed of many strings of PV array modules, connected in parallel, in order to provide the desired power (i.e., output voltage and current). This solar power converter exhibits a nonlinear \((I_{pv} - V_{pv})\) characteristics given, approximately, by the following equation:

\[
I_{pv} = N_p \left( I_{ph} - I_s \exp\left(\frac{qV_{pv}}{nK_BT}\right) - 1 - \frac{V_p}{nR_{sh}}\right),
\]

where \(I_{pv}\) and \(V_{pv}\) are the PV generator current and voltage, respectively, \(N_p\) is the number of PV modules connected in series, and \(N_p\) is the number of parallel paths.

Note that the PV array terminal voltage and the output current have nonlinear characteristics due to the presence of the exponential term as shown in Equation (3). The power-voltage-irradiation 3D characteristics for the PV array at the temperature 25°C and power-voltage-temperature 3D characteristics for an irradiation of 1 kW/m² are displayed in Figure 3.

2.1.2. DC/DC Boost Converter Model. In this subsection, the state space averaged modeling of DC/DC boost converter (Figure 4) is presented. The PV modules are connected to DC-link using a DC/DC converter which consists of a semiconductor (insulated gate bipolar transistor “IGBT”), a diode (for bidirectional current flow mode), and a passives element. Applying Kirchhoff’s laws and averaging technique,

\[
\frac{dV_{pv}}{dt} = \frac{1}{C} (I_{pv} - I_L),
\]

\[
\frac{di_L}{dt} = \frac{1}{L_1} v_{pv} - \frac{1}{L_1} v_{dc},
\]

\[
\frac{dv_{dc}}{dt} = \frac{1}{C} (1 - \alpha) I_L - \frac{1}{C} I_{dc}.
\]

It is clear that one can easily deduce from (4b) that the ratio between input voltage (PV voltage \(v_{pv}\)) and output (DC-Link \(v_{dc}\)), in steady-state, can be written as follows:

\[
v_{dc} = \frac{1}{1 - \alpha} v_{pv}.
\]

2.2. PMSG Aerogenerator-AC/DC Association Modelling

2.2.1. Wind Turbine Model. The wind power acting on the swept area of the blade \(A = \pi R^2\) (perpendicular to the wind speed direction) is a function of the air density \(\rho\) (kg/m³) and the wind velocity \(V_w\) (m/s). The transmitted power \(P_T\) (W) is generally deduced from the wind power, using the power coefficient \(C_p\). The transmitted power according to
the rotor synchronous aerogenerator speed for various values of the wind speed can be expressed as follows [25, 32, 34]:

\[ P_T = \frac{1}{2} C_p(\lambda, \beta) \rho \pi R^2 V_w^3. \]  

(6)

The power coefficient \( C_p \) is a nonlinear function of the tip-speed-ratio \( \lambda = R \Omega_T / V_w \) (with \( R \) denotes the turbine radius) which depends on the wind velocity \( V_w \) and the rotation speed of the generator rotor \( \Omega_T \) (rd/s) and blade pitch angle \( \beta \). The power coefficient \( C_p \) can be expressed as [8]

\[
\begin{align*}
C_p(\lambda, \beta) &= c_1 \left( \frac{c_2}{\lambda} - c_3 \beta - c_4 \right) e^{-\left(\frac{c_5}{\lambda}\right)} + c_6 \lambda, \\
1 &= \frac{1}{\lambda + 0.08 \beta} - \frac{0.035}{\beta^2 + 1},
\end{align*}
\]

(7)

where the values of the parameters \( c_i \) of the power coefficient nonlinear function are presented in Table 1.

According to Betz’s theory, ideally, only 59.3% of the available power can be extracted [8]. A wind turbine considered in this paper has a curve of the power coefficient \( C_p \) presented in Figure 5. The wind turbine characteristics are assembled in Table 2.

Note that the maximum power coefficient \( C_{p, \text{opt}} \) for each turbine angle pitch \( \beta \), depends of the tip speed ratio \( \lambda \). In effect, there exist a \( \lambda = \lambda_{\text{opt}} \), such that

\[ \max \left( C_p(\lambda, \beta) \right) = C_p(\lambda_{\text{opt}}, 0) = 0.48 \text{ with } \lambda_{\text{opt}} = 8.1. \]

(8)

The mechanical torque of the turbine \( T_T \) is given by

\[ T_T = \frac{P_T}{\Omega_T} = \frac{C_p(\lambda, \beta) \rho \pi R^3 V_w^2}{\lambda}. \]

(9)

2.2.2. Synchronous Aerogenerator Modelling. The controlled WEC system is illustrated by Figure 1. The synchronous aerogenerator subsystem structure consists of a permanent magnet synchronous generator (PMSG) and the AC/DC boost rectifier. The converter switches are operating according to the known pulse width modulation principle. The rectifier circuit is shown in Figure 6. It contains six IGBTs, with antiparallel diodes, connected in bridge mode. The three-phase symmetrical sine can be converted into two DC components by the well-known Park transformation. These new rotating reference system components are more suitable for developing control laws [12, 14].

Accordingly, all sinusoidal signals are transformed into continuous quantities along the \( d \)-axis or the \( q \)-axis. According to [12, 23], the electrical behavior of the association PMSG-AC/DC, expressed in the \( dq \)-coordinates, can be given the following state-space form where the direction of the permanent magnet vector is aligned with the \( d \)-axis.

\[
\begin{align*}
v_{id} &= R_s i_{id} + L_s \frac{di_{id}}{dt} - L_d \omega i_{iq}, \\
v_{sq} &= R_s i_{sq} + L_s \frac{di_{sq}}{dt} + L_d \omega i_{iq} + \Phi_m \omega_c.
\end{align*}
\]

(10a)

(10b)
Permanent magnets in the stator phase; and "following state-space representation of the associated simulation (PWM) period. Then, the model (10) generates the voltage and current in \( \text{d} \)-coordinate coordinates (Park transformation of three-phase stator voltage vector), respectively; \( R_s \) and \( L_s \) are the stator resistance and inductance; \( \Phi_m \) the magnetic flux amplitude induced by the rotor permanent magnets in the stator phase; \( J \) is the total rotor inertia, viscous coefficient, and number of poles pairs, respectively; \( \Omega \) is the angular rotor speed; \( T_g \) is the aerodynamic torque.

Now, let us introduce the state variables \( x_1 = \Omega, x_2 = i_{sq}, \) and \( x_3 = i_{sd} \), where \( x_i \) denotes the average value on the modulation (PWM) period. Then, the model (10) generates the following state-space representation of the associated “PMSG generator-rectifier.”

\[
\begin{align*}
J \frac{d\Omega}{dt} &= T_g - T_e - F_\Omega, \quad (10c) \\
T_e &= \frac{3}{2} p \Phi_m i_{iq}, \quad (10d)
\end{align*}
\]

where \( (v_{sd}, v_{sq}) \) \((i_{sd}, i_{sq})\) denote the averaged components of three-phase duty cycle system (\( s_{a}, s_{b}, s_{c} \)). Note that \( s_i (i = a, b, c) \) is the switch position function taking values in the discrete set \([0, 1]\). Specifically,

\[
S_i = \begin{cases} 
1 & \text{If } S_a = \text{‘ON’ And } S_b = \text{‘OFF’}, \\
0 & \text{If } S_a = \text{‘OFF’ And } S_b = \text{‘ON’}.
\end{cases}
\]

The AC/DC converter is featured by the fact that both components of the stator (i.e., \( d \)-voltage and \( q \)-voltage) can be controlled independently. For this reason, these voltages are expressed as a function of the corresponding control action (see, e.g., [12]):

\[
\begin{align*}
v_{sd} &= v_{dc} u_{sd}, \quad (12a) \\
v_{sq} &= v_{dc} u_{sq}, \quad (12b) \\
i_R &= u_{ad} i_{ad} + u_{aq} i_{aq}. \quad (12c)
\end{align*}
\]

where \( u_{sd} \) and \( u_{sq} \) represent the \( d \)-axis and \( q \)-axis components of three-phase duty cycle system \( (s_{a}, s_{b}, s_{c}) \). Now, let us introduce the new notation of state variables:

\[
x = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = \begin{pmatrix} \Omega \\ i_{ad} \\ i_{aq} \end{pmatrix} \quad \text{and} \quad u = \begin{pmatrix} u_{ad} \\ u_{aq} \end{pmatrix}.
\]

Then, substituting (14) in (11) yields the following state-space representation of the “PMSG-AC/DC association”:
2.2.3 Modelling of the Combination of Three-Phase AC/DC/AC Converter and the Grid. The three-phase inverter circuit (DC/AC) is presented in Figure 7. The power supply net is connected to a converter which consists of a converter that has 6 semiconductors.

Applying Kirchhoff’s laws and Park transformation, this subsystem is portrayed by the following set of differential conditions [9, 29, 35]:

\[
\begin{align*}
\dot{x}_1 &= \frac{T_{g}}{J} - \frac{F}{J} x_1 - \frac{3}{2} \frac{p}{J} \Phi_m x_2, \\
\dot{x}_2 &= \frac{1}{L_s} u_2 - \frac{R_s}{L_s} x_2 - \omega_c x_3 - \frac{\Phi_m}{L_s} \omega_c, \\
\dot{x}_3 &= \frac{1}{L_s} u_1 - \frac{R_s}{L_s} x_3 + \omega_c x_2.
\end{align*}
\]

where \((e_{gd}, e_{gq}, (i_{gd}, i_{gq}), (u_{gd}, u_{gq}))\) denote the averaged network voltage and current and input control of the inverter in dq-coordinate (Park’s transformation).

Using the power conservation principle, one has \(P_{\text{load}} = P_{\text{OUT}}\) or, equivalently, \(v_{dc} i_i = E_{gd} i_{gd} + E_{gq} i_{gq}\). Also, from (16), one immediately gets that [23]

\[
\begin{align*}
2 v_{dc} \frac{dv_{dc}}{dt} &= \frac{1}{C} e_{gd} i_{gd} - \frac{1}{C} (e_{gq} i_{gq} - v_{dc} i_R), \\
\frac{di_{gd}}{dt} &= -\frac{1}{L_g} e_{gd} + \omega_c i_{gq} + \frac{1}{L_g} u_{gd} v_{dc}, \\
\frac{di_{gq}}{dt} &= -\frac{1}{L_g} e_{gq} + \omega_c i_{gd} + \frac{1}{L_g} u_{gq} v_{dc}.
\end{align*}
\]
Let us present the state factors

\[ x_4 = v_{dc}, \quad x_5 = i_{gd}, \quad x_6 = i_{gq}, \]

\[ u_3 = u_{gd}, \quad u_4 = u_{gq} \]

represent the average \( d \)- and \( q \)-axis components of the triphase duty ratio system \( \theta_g \). The state-space conditions gotten up to presently are put together to induce a state-space demonstration of the total framework. For future reference, the full demonstration is modified here:

\[ \dot{x}_1 = \frac{T_d}{L} - \frac{F}{L} x_1 - \frac{3 p \Phi_m}{2 J} x_2, \quad (18a) \]

\[ \dot{x}_2 = \frac{1}{L_s} u_1 - \frac{R}{L_s} x_2 - \omega_e x_3 - \left( \frac{\Phi_m \omega_e}{L_s} \right), \quad (18b) \]

\[ \dot{x}_3 = \frac{1}{L_s} u_1 - \frac{R}{L_s} x_3 + \omega_e x_2, \quad (18c) \]

\[ \dot{x}_4 = \frac{1}{C} e_{gd} x_5 - \frac{1}{C} \left( e_{gq} x_6 - v_{dc} \right), \quad (18d) \]

\[ \dot{x}_5 = \frac{1}{L_g} e_{gd} + \omega_e x_6 + \frac{1}{L_g} v_{dc} u_3, \quad (18e) \]

Figure 8: Control system including the DC/AC converter and line grid.

Figure 9: Characteristics of the PV panel, with constant temperature \( T = 45°C \) and varying radiation \( G \) and the optimal power-voltage characteristic from the interpolation of point.

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\[ \dot{x}_2 = \frac{1}{L_s} u_1 - \frac{R}{L_s} x_2 - \omega_e x_3 - \left( \frac{\Phi_m \omega_e}{L_s} \right), \quad (18b) \]

\[ \dot{x}_3 = \frac{1}{L_s} u_1 - \frac{R}{L_s} x_3 + \omega_e x_2, \quad (18c) \]

\[ \dot{x}_4 = \frac{1}{C} e_{gd} x_5 - \frac{1}{C} \left( e_{gq} x_6 - v_{dc} \right), \quad (18d) \]

\[ \dot{x}_5 = \frac{1}{L_g} e_{gd} + \omega_e x_6 + \frac{1}{L_g} v_{dc} u_3, \quad (18e) \]
\[
\dot{x}_6 = -\frac{1}{L_g} e_{gq} - \omega_g x_3 + \frac{1}{L_g} v_{dc} u_4.
\]  
(18f)

3. Proposed Control Design

3.1. Control Objectives. In this section, the aim is to construct a nonlinear control strategy able to carry out the four following control objectives.

Objective 1. Extracted solar power optimization: PV voltage \(v_{pv}\) must track as accurately as possible a signal reference \(v_{pv-ref}\) generated by an optimizer called power to optimal voltage (POV) [23]. This makes it possible to achieve an operating of PV corresponding to maximum power point tracking (MPPT).

Objective 2. Generated wind power optimization: the stator current of the synchronous aerogenerator should be controlled to adjust the rotor speed to a given time-varying reference signal \(\Omega_{opt}\) generated by power to optimal speed (POS) optimizer [7], despite the wind velocity variations.

Objective 3. Controlling the DC-link voltage: making \(v_{dc}\) track a given reference signal \(v_{dc-ref}\).

Objective 4. Power factor correction (PFC) requirement: the electrical network must be sinusoidal with the frequency as the electrical voltage network, and the reactive power must be always zero.

In order to achieve these control objectives, a nonlinear state feedback controller will now be designed in the next subsections.

3.2. Boost Converter Controller. In this section, to achieve Objective 1, the state space average model of DC/DC converter (4) will be useful for designing the sliding mode controller (SMC). The purpose of this controller is to force the PV voltage to track a signal reference generated by POV optimizer.

We are seeking out the realization of a voltage reference optimizer that meets the MPPT requirement. Specifically, the optimizer must calculate the ideal voltage estimate \(v_{pv-ref}\) so that the voltage \(v_{pv}\) follows it correctly; the most extreme control is captured and transmitted to the grid through the sliding mode controller.

Currently, the plan of the voltage reference optimizer is based on the power-voltage characteristic of Figure 8 and the fact that it does not require the irradiation measurement. The characteristics used are those obtained at 45°C temperature where the photovoltaic generator operates most of the time.

The vertices of these curves give the maximum extractable power \(P_{pv-max}\) and therefore represent the optimal point. Each of these points is characterized by the optimal voltage \(v_{pv}\). It is easy to see from Figure 9 that for any irradiation \(G\) value, there is a unique coupling \(((V_{pv}, P_{pv})\), involving the maximum extractable power. Many such points have been collected and interpolated to obtain a polynomial function \(v_{pv-ref} = f(P_{pv-max})\). The polynomial thus constructed is expressed as

\[
v_{pv-ref} = f(P_{pv-max}) = \sum_{k=0}^{n} a_k P_{pv-max}^k.
\]  
(19a)

where \(a_k\) coefficient values correspond to the characteristic of the used PV generator.

Remark 1. The polynomial interpolation of the generating function is obtained by using the Matlab functions POLYVAL, SPLINE, and POLYFIT. The input of the optimizer is the product of the measured voltage \(v_{pv}\) and the measured current \(i_{pv}\), and the output of the optimizer is the optimal voltage using the predefined polynomial (19a).

The aim is to control a boost transistor to extract maximum power from photovoltaic panels. Let us introduce the power expression issued from the photovoltaic panels:

\[
P_{pv} = i_{pv} v_{pv}. \tag{19b}
\]

The evolution of this power as a function of the current is given, based on Equations (1)–(3), by Figure 3.

The peak value of this power, as you can see in Figure 3, is given by the operating point solution of its derivative over the voltage:

\[
\frac{\partial P_{pv}}{\partial v_{pv}} = i_{pv} + v_{pv} \frac{\partial i_{pv}}{\partial v_{pv}}. \tag{20}
\]

This value must be zero to ensure the MPPT requirement. Let us define the switching function \(S\) (i.e., mathematical equation of the sliding surface) defined as

\[
S = i_{pv} + v_{pv} \frac{\partial i_{pv}}{\partial v_{pv}}. \tag{21}
\]

By applying the variation principle, the derivative of this expression vanishes if the control input \(\alpha\) is equal to its equivalent value \(\alpha_{eq}\). This is knowing that the BOOST command is a linear composition of two expressions:

(i) Equivalent control input \(\alpha_{eq}\) used on the sliding surface

(ii) Robust switching control input \(\alpha_n\) used to bring the operating point back to this sliding surface

\[
\dot{S} = \frac{\partial S}{\partial x}^T \dot{x} = \frac{\partial S}{\partial x}^T \frac{d}{dt} \left[ \begin{array}{c} i_L \\ v_{dc} \end{array} \right]. \tag{22}
\]

The derivative of \(S\) over \(v_{dc}\) is null; thus,

\[
\frac{\partial S}{\partial i_L} \frac{di_L}{dt} = \frac{\partial S}{\partial i_L} \left( \frac{V_{pv}}{L_1} - (1 - \alpha) \frac{v_{dc}}{L_1} \right). \tag{23}
\]

This expression vanishes if \(\alpha = \alpha_{eq}\), then

\[
\alpha_{eq} = 1 - \frac{V_{pv}}{V_{dc}}. \tag{24}
\]
The switching signal can simply be taken equal to

$$\alpha_n = \rho \cdot \text{sign}(S) = \begin{cases} +\rho, & \text{if } S > 0, \\ 0, & \text{if } S = 0, \\ -\rho, & \text{if } S < 0. \end{cases} \quad (25)$$

Using the following Lyapunov equation $V_1 = (1/2)S^2$, its derivative can be written as

$$\dot{V}_1 = S \dot{S}. \quad (26)$$

Using Equation (23) and knowing that

$$\alpha = \alpha_{eq} + \alpha_n, \quad (27)$$

one can write

$$\dot{V}_1 = S \frac{\partial S}{\partial i_L} \left( \frac{\partial V_d}{\partial i_L} \frac{V_{dc}}{L_1} \right) + \frac{\partial S}{\partial i_L} \frac{\partial V_d}{\partial i_L} \rho[S]. \quad (28)$$

$V_{dc}/L_1$ is all time a positive value, and $(\partial S/\partial i_L) = (\partial S/\partial i_{p_r})$, $(\partial i_{p_r}/\partial i_L) = (2(\partial i_{p_r}/\partial i_{p_r}) + V_p(p^2 i_{p_r}/\partial i_{p_r}^2))(\partial i_{p_r}/\partial i_L)$ is all time a positive value, then the sliding mode controller is globally asymptotically stable, and the parameter value $\rho$ (always taken negative) allows the adjustment of the dynamic parameters of the controller. Its value can be deduced using the try and error method.

### 3.3. PMS Aerogenerator Controller

#### 3.3.1. Rotor Speed Loop (MPPT)

The purpose is to maximize wind energy capture and achieve maximum point power tracking (MPPT). For this, the top speed ratio is set to its optimum value $\lambda_{opt}$ which contributes to the peak power coefficient $C_{max}$ as shown in Figure 5(b). Therefore, the optimum rotor speed of the wind turbine can be written as follows:

$$\Omega_{opt} = \frac{\lambda_{opt} V_w}{R}. \quad (29)$$

Thus, the maximum output power of the wind turbine can be expressed as:

$$P_{max} = k_{opt} \Omega_{opt}^3, \quad (30)$$

where $k_{opt} = (1/2)C_{max} \rho S(R/\lambda_{opt})^3$.

The control objective is to track the reference speed $\Omega_{opt}$ obtained by the POS optimizer [7], with the rotor speed $x_1$, where $u_2$ stands as the actual input; the speed control loop is based on Equations (18a) and (18b). By following the technique of backstepping [35], we consider the $e_1$-error followed by speed:

$$e_1 = x_1 - \Omega_{ref} = x_1 - x_1^* \quad (31)$$

In view of (18a), the above error undergoes the following equation:

$$\dot{e}_1 = -\frac{F}{J} x_1 - \frac{K_t}{J} x_2 + \frac{T_d}{J} - x_1^* \quad (32)$$

In (31) and (32), one can consider the quantity $\alpha = -(K_t/f)x_2$ as a virtual control input for the $e_1$-dynamics. The stabilizer function associated with $\alpha$ can be denoted $\alpha^*$ (yet to be determined). It is easily seen from ((34)) and ((35)) that if $\alpha = \alpha^*$ with
\[
\alpha^* = \left(-c_1e_1 + \frac{F}{T}x_1 - \frac{T_d}{T} + \dot{x}_1^*\right), \tag{33}
\]

with \(c_1 > 0\) as a controller plan parameter.

If \(\alpha = \alpha^*\), one will have \(\dot{e}_1 = -c_1e_1\) which is asymptotically stable concerning the Lyapunov function \(V_2 = 0.5e_1^2\). In effect, we will then have
\[
\dot{V}_1 = e_1\dot{e}_1 = -c_1e_1^2 < 0. \tag{34}
\]

As \(\alpha = -(\mathcal{K}_f/J)x_2\) is a virtual control input, one cannot set \(\alpha = \alpha^*\). Then, a new error is introduced, which depends on the quadrature current:
\[
e_2 = \alpha - \alpha^*. \tag{35}
\]

Using Equations (33), (34), and ((35)), it follows from (33) that the dynamic error \(e_1\) undergoes the following equation:
\[
\dot{e}_1 = -c_1e_1 + e_2. \tag{36}
\]

The next step is to make the error system \((e_1, e_2)\) asymptotically stable. So, let us get the error \(e_1\) trajectory to determine the command input \(u_2\). Determining this with regard to time and utilizing Equations (34) and ((35)) gives
\[
\dot{e}_2 = -\left(\frac{K_f}{J}\right)e_2 - \dot{\alpha}^*. \tag{37}
\]

Using (34), ((35)), (18a), and (18b) in (36), one gets:
\[
\dot{e}_2 = -c_1^2e_1 + c_1e_2 + \frac{K_f}{JL_4}u_2v_{dc} + f(x_1, x_2, x_3), \tag{38}
\]

where
\[
f(x_1, x_2, x_3) = \frac{K_f}{J} \left(\frac{R_4}{L_4}x_2 + px_1x_3 - \frac{K_f}{J}x_1\right) + \left(\frac{F}{T}x_1 + \frac{F_K}{T}x_3\right) - \frac{FT_d}{T} + \frac{T_d}{T} - \dot{x}_1. \tag{39}
\]

The dynamic error Equations (34), ((35)), and (36) receive the following simplified form:
\[
\dot{e}_1 = -c_1e_1 + e_2, \tag{40a}
\]
\[
\dot{e}_2 = -c_1^2e_1 + c_1e_2 + \frac{K_f}{JL_4}u_2v_{dc}f(x_1, x_2, x_3). \tag{40b}
\]

To determine an input control law for (40b), let us consider:
\[
V_3 = V_2 + \frac{1}{2}e_2^2 = \frac{1}{2}e_1^2 + \frac{1}{2}e_2^2. \tag{41}
\]

Using (41), the time derivative of \(V_3\) can be effortlessly modified as:

**Table 3: PVECS characteristics.**

| Electrical characteristics of the solar module | 60.53 W |
|---|---|
| Maximum power \(P_{\text{max}}\) | 60.53 W |
| Open circuit voltage \(V_{\text{oc}}\) | 21.1 V |
| Short circuit current \(I_{\text{sc}}\) | 3.8 A |
| Voltage at maximum power point \(V_{\text{mp}}\) | 17.04 V |
| Current at maximum power point \(I_{\text{mp}}\) | 3.5 A |
| Cells per module \(N_{\text{cell}}\) | 36 |
| Boost converter characteristics | |
| PV condensator \(C_{\text{pv}}\) | 0.1 mF |
| Boost converter inductance \(L_i\) | 3 mH |
| Modulation frequency | 10 kHz |

\[
\dot{V}_3 = -c_1e_1^2 + e_2e_1 + e_2\dot{e}_2. \tag{42}
\]

For the \((e_1, e_2)\)-system to be clearly asymptotically stable, it is sufficient to apply the control \(u_2\) so as to ensure that
\[
\dot{V}_3 = -c_2e_1^2 - c_2e_2^2, \tag{43}
\]

where \(c_2 > 0\) is a new controller model parameter.

In view of Equations (34), ((35)), and (36) is guaranteed on the off chance that
\[
\dot{e}_2 = -c_2e_2 - e_1. \tag{44}
\]

Comparing (42) and (40b) yields the control law:
\[
u_2 = -fL_i \left(\frac{c_1 + c_2}{3.5K_f} - \frac{1}{3.5K_f}\right)x_3 + f(x_1, x_2, x_3). \tag{45}
\]

3.3.2. d-Axis Current Regulation. The next control objective is to optimize the stator aerogenerator control \(i_{sd}\) component must be tracking the reference signal \(i_{sd-ref} = 0\). The d-axis current \(x_3\) that undergoes (15c) in which the quantity is noted as
\[
\dot{\beta} = px_2x_1 - \frac{v_{dc}}{L_s}u_1. \tag{46}
\]

As the reference \(i_{sd-ref}\) is considered a null signal, it follows that the tracking error \(e_3 = x_3 - i_{sd-ref}\) undergoes the dynamic:
\[
\dot{e}_3 = -\frac{R_4}{L_s}e_3 + \beta. \tag{47}
\]

Consider the quadratic Lyapunov function \(V_4 = (1/2)e_3^2\). It is effectively checked on the off chance that the virtual control is let to be
\[
\beta = -\left(-\frac{R_4}{L_s} + c_3\right)e_3, \tag{48}
\]
where $c_3 > 0$ (a new model parameter), after that,

$$\dot{V}_4 = -c_3 e_3^2,$$  \hspace{1cm} (49)  

which is defined negative. Moreover, by substituting Equations (49) in (47), we have the closed loop equation

$$\dot{e}_3 = -c_3 e_3.$$  \hspace{1cm} (50)  

Now, the actual control input can be obtained by replacing Equation (48) into (46) and solving the resulting equation for $u_3$. In doing so, we obtain

$$u_3 = \left( c_3 e_3 - \left( \frac{R}{L_s} \right) e_3 + px_2x_1 \right) \frac{L_s}{V_{dc}}.$$  \hspace{1cm} (51)  

In the following proposition, the control closed loops induced by the speed and $d$-axis current control laws (39) and (51) as a consequence are analysed.

**Proposition 2.** Consider the control system consisting of the subsystem (18a)–(18c) and the control laws (33), (45), and (51). The resulting closed-loop system undergoes, in the $(e_1, e_2, e_3)$-coordinates, the following equation:

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \end{bmatrix} = B_1 \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} \text{ with } B_1 = \begin{bmatrix} -c_1 & 1 & 0 \\ -1 & -c_2 & 0 \\ 0 & 0 & -c_3 \end{bmatrix}. \hspace{1cm} (52)$$  

This equation defines a globally exponentially stable system $V = 0.5(e_1^2 + e_2^2 + e_3^2)$ ($B_1$ is Hurwitz), and the error
vector \((e_1, e_2, e_3)\) converges exponentially fast to zero, regardless of initial conditions.

Proof. Equation (52) is specifically gotten from Equations (34), ((35)), (40a), and (50).

The control to optimize the operation of the wind generator explained before is described in the block diagram of Figure 10.

3.4. Grid Side Converter Control. By controlling a PFC, the principal purpose is to obtain a sinusoidal grid line current/voltage and the active power injection into the electrical grid, by providing \(Q_g = 0\) VAR. The continuous voltage of DC-link \(v_{dc}\) ought to track a given reference signal \(v_{dc-ref}\). These objectives give rise to two control closed-loops. The first loop ensures the regulation of the DC voltage and the second ensures the PFC exigency.

Using the well-known the backstepping technique [17], let us consider the following tracking error \(e_4\):

\[
e_4 = x_4 - v_{dc-ref}^4 = x_4 - x_4^*,
\]

In view of Equation (18d), the above-mentioned error submits to the following equation:
The quantity \( \gamma = (1/c)E_{gdx}x_5 \) rises up as a virtual control for the subsystem of Equation (54). Let us consider \( \gamma^* \) as stabilizing function associated to \( \gamma \).

\[
\gamma^* = \left( -c_4 \epsilon_4 + \frac{1}{C} \left( E_{gdx}x_6 - v_{dc}i_R \right) + \dot{x}_4^* \right).
\]  

(55)

\( c_4 > 0 \) is a model parameter. Indeed, if \( \gamma = \gamma^* \), one will have \( \dot{\epsilon}_4 = -c_4 \epsilon_4 \) which clearly is \( \dot{z}_3 = -c_3z_3 \) asymptotically stable with respect the Lyapunov function \( V_5 = 0.5\epsilon_4^2 \). So, one then has

\[
V'_5 = 0\epsilon_4 < 0.
\]  

(56)

As \( \gamma = (1/c)E_{gdx}x_5 \) is just a virtual control input, one cannot set \( \gamma = \gamma^* \). Then, a new error is introduced:

\[
e_5 = \gamma - \gamma^*.
\]  

(57)

Using (54), (55), and (57), the \( c_4 \)-dynamic undergoes the following equation:

\[
\dot{e}_5 = -c_4 \epsilon_4 + e_5.
\]  

(58)
The next step consists in determining the control input \( u_3 \) ensuring asymptotic stability of \((e_4, e_5)\) errors. Proceeding firstly, let obtain through the use of Equation (57), the tracking trajectory of the \( e_5 \)-error:

\[
\dot{z}_2 = \frac{1}{C} e_{\text{gd}} \dot{x}_5 - \dot{y}^*.
\]  

(59)

Using (55) and (18d) in (59), one gets

\[
\dot{z}_2 = -c_1^2 e_4 + c_4 e_5 + \frac{e_{\text{gd}}}{C L_g} v_{\text{dc}} u_3 + g(x_4, x_5, x_6),
\]  

(60)

where

\[
g(x_4, x_5, x_6) = \frac{e_{\text{gd}}}{C} \omega_{F} x_6 + \frac{d}{dt} \left( \frac{1}{C} (e_{\text{gd}} x_6 - v_{\text{dc}} \gamma_k) \right) - \ddot{x}_4^*.
\]  

(61)

Let us consider the quadratic Lyapunov function candidate to determine a stabilizing control law for Equation (60).

\[
V_6 = V_5 + \frac{1}{2} e_4^2 = \frac{1}{2} e_4^2 + \frac{1}{2} e_5^2.
\]  

(62)
Then, $V_6 = -c_4 e_4^2 + e_4 e_5 + e_5 \dot{e}_5$. 

This prove that, for the $(e_4, e_5)$-system to be considerate asymptotically stable, it is appropriate to select the control $u_3$ in order that

$$\dot{V}_6 = -c_4 e_4^2 - c_5 e_5^2,$$  \hspace{1cm} (64)

where $c_5 > 0$ is a new design parameter. In view of (63), Equation (64) is ensured if

$$\dot{e}_5 = -c_5 e_5 - e_4.$$  \hspace{1cm} (65)

Correspondingly, the two Equations (60) and (65) yields to the following backstepping control law:

$$u_3 = \frac{C.L_u}{e^{gd} V_{dc}} \cdot (e_4^2 - (c_4 + c_5)e_5 - g(x_4, x_5, x_6)).$$  \hspace{1cm} (66)
The next control objective implicates the reactive power $Q_g$ which requisite to follow its reference $Q_g^*$. The injected reactive power into the grid is given by the equation:

$$Q_g = e_{gd}x_6 - e_{gq}x_5. \quad (67)$$

The corresponding tracking error is denoted:

$$e_6 = Q_g - Q_g^*. \quad (68)$$

In view of (18c) and (18f), the above error undergoes the following equation:

$$\dot{e}_6 = \frac{v_{dc}}{L_g} (e_{gd}u_4 - e_{gq}u_3) - \omega_g (e_{gd}x_5 + e_{gq}x_6) - \dot{Q}_g^*. \quad (69)$$

We are able to utilize a basic proportional control law to urge a stabilizing control flag for this first-order system. We can use a simple proportional control law to reach a steady control signal for this first-order model system.

$$\frac{v_{dc}}{L_g} (e_{gd}u_4 - e_{gq}u_3) = -c_6 e_6 + \omega_g (e_{gd}x_5 + e_{gq}x_6) + \dot{Q}_g^*, \quad (70)$$
where $c_6 > 0$. So, from (70), one gets

$$u_4 = \frac{I_g}{e_{gd}} \left( -c_6 e_6 + \omega_g \left( e_{gd} x_5 + e_{gq} x_6 \right) + \dot{Q}_g \right).$$  \hfill (71)

The proposed closed loop control created by the DC-link voltage and reactive power control laws accordingly, defined by Equations (66) and (71), are discussed in the following proposition.

**Proposition 3.** Consider the control system consisting of the subsystem (18d)–(18f) and the control laws (66) and (71). The resulting closed-loop system undergoes, in the $(e_4, e_5, e_6)$-coordinates, the following equation:

$$\begin{pmatrix} \dot{e}_4 \\ \dot{e}_5 \\ \dot{e}_6 \end{pmatrix} = B_2 \begin{pmatrix} e_4 \\ e_5 \\ e_6 \end{pmatrix} \text{with } B_2 = \begin{pmatrix} -c_4 & 1 & 0 \\ -1 & -c_5 & 0 \\ 0 & 0 & -c_6 \end{pmatrix}.$$  \hfill (72)

This equation defines a globally exponentially stable system $V = 0.5(e_4^2 + e_5^2 + e_6^2)$ ($B_2$ is Hurwitz), and the error vector $(e_4, e_5, e_6)$ converges exponentially fast to zero, whatever the initial conditions.

**Proof.** Equation (72) is directly obtained from Equations (58), (65), and (69). □

The control developed before for the management and the optimization of the electrical energy injected into the grid is described in the block diagram of Figure 8.

### 4. Simulation Results

The experimental setup of the HREC system (Figure 1) has been simulated using MATLAB/Simulink resources. The proposed nonlinear controllers (27), (51), (66), and (71) are now evaluated, through simulation. The HREC characteristics are summarized in Tables 2 and 3.

The feedback controller performances will be evaluated in the presence of time-varying (Figure 11) and wind speed profile described by Figure 12. The applied solar irradiation and wind speed are chosen so that the solar energy conversion subsystem operates in low, medium, and high solar irradiation, and the aerogenerator works in different wind velocity zones.

The designed controllers regulate the PV voltage and turbine speed to the optimal values tuned online to maximize the extracted power. The reference signals are calculated, using the generated active powers of the HRECs; the POV and POS optimizers, designed in [7, 26], generate the PV voltage and turbine speed references.

The design parameters are given in the following values that proved to be appropriate:

$$\begin{align*}
c_1 &= 0.98; \ c_2 = 432.08; \ c_3 = 49.74; \ c_4 = 200; \ c_5 = 243; \ c_6 = 547.
\end{align*}$$  \hfill (73)

#### 4.1. Illustration of the PV Subsystem Controller Performances.

The PV-DC/DC subsystem controller developed in Section 3.2 will be evaluated by simulation. The irradiation variation is chosen for two extreme values, low irradiation $G = 100$ W/m$^2$, medium $G = 500$ W/m$^2$, and high value $G = 1000$ W/m$^2$ which are illustrated in Figure 11. The simulation is carried out at a temperature $T = 25^\circ$C. The characteristics of the simulated PV-DC/DC subsystem are summarized in Table 3.
The proposed SMC tracks greatly approximately to the MPPT. The PV voltage \( V_{pv} \) converges quickly, as shown by Figure 13, to its reference \( V_{pv-ref} \) generated by the P0V optimizer. Its value varies with the power extracted \( P_{pv} \), and the tracking error \( (V_{pv-ref} - V_{pv}) \) vanishes less than 0.1 s (see Figure 13). Consequently, the power extracted from the PV module, as shown by Figure 14, is always maximal regardless to radiation value \( G \).

Figure 15 shows the photovoltaic module current \( I_{pv} \). It is observed that the current amplitude changes whenever the radiation \( G \) varies.

4.2. Illustration of the Aerogenerator Subsystem Controller Performances. The controlled WEC subsystem is simulated using the electro-mechanical characteristics of Table 2. According to the control design in sections (4.3 and 4.4), the remaining closed-loop inputs are kept constant, namely, \( i_{sd-ref} = 0 \); \( V_{dc-ref} = 1200 \) V; \( Q_{g-ref} = 0 \) K var.

In this subsection, the WECS performances are illustrated by Figures 12 and 16–23. The considered wind speed profile is shown in Figure 12. It is seen that wind velocity varies randomly over a wide range. In response to the chosen wind speed profile, the turbine generates the active power as shown in Figure 17. Accordingly, Figure 16 shows the wind speed signal reference generated by the POS algorithm [7–37]. Referring to the turbine power characteristics (Figure 5), these active power corresponds to the optimal values of each wind speed.

Figures 17–19 show that the mechanical rotor speed \( \Omega \) and the \( d \)-axis of the stator current \( i_{sd} \) perfectly converge to their respective references. The tracking quality is quite satisfactory after each change in the wind speed.

Figure 20 shows that the DC-link voltage \( V_{dc} \) is perfectly regulated. The reactive power injected into the grid \( Q_{d} \) (equals zero) is showed in Figure 22. Figure 23 shows that the wave frame of the line current is all time sinusoidal and in phase with the grid current complying with the PFC requirement.

5. Conclusion

We have addressed the problem of nonlinear control of the hybrid renewable energy conversion system. Optimal wind and solar energy extraction are achieved in variable wind speed and solar irradiation without using the wind velocity and irradiation sensors. The controlled system is an association including wind turbine, synchronous aerogenerator, and power converters. Firstly, a PV voltage loop-based integral sliding mode controller is designed to achieve the solar maximum power point tracking. Then, a nonlinear backstepping controller is proposed to ensure the control objectives: (i) the wind power MPPT and (ii) power factor correction (PFC). It has been illustrated that the proposed state feedback controller ensures, in addition to MPPT and PFC objectives, tight regulation of the stator \( d \)-axis current as well-regulated the DC-link voltage. The obtained results clearly demonstrate that all control objectives are achieved with high performances and robustness of the proposed nonlinear state feedback control.

Nomenclature

| Symbol | Description |
|--------|-------------|
| \( V_w \) | Wind speed (m/s) |
| \( R \) | Blade radius (m) |
| \( \rho \) | Air density (Kg/m³) (\( \rho = 1.225 \) Kg/m³) |
| \( C_p(\lambda, \beta) \) | Power coefficient |
| \( \lambda \) | Tip speed ratio |
| \( \beta \) | Pitch angle (°) |
| \( p \) | Pole pairs number |
| \( s \) | Laplace operator |
| \( \Omega_T \) | Turbine rotational speed (rad/s) |
| \( T_m \) | Turbine mechanical torque (N.m) |
| \( L_{dc} \) | DC-Link voltage and current |
| \( I_{sd} \), \( I_{sq} \) | Direct and quadratic stator fluxes (Wb) |
| \( \Phi_m \) | Magnet flux (Wb) |
| \( R_s \) | Stator resistance (Ω) |
| \( \omega_e \) | Electrical pulsatation (rad/s) |
| \( V_{pv} \), \( I_{pv} \) | PV array voltage and current, respectively |
| \( I_{ph} \) | Photonic current (A) |
| \( I_{r} \) | Reverse saturation current of the diode |
| \( q \) | Electron charge (\( q = 1.6 \cdot 10^{-19} \) C) |
| \( K_B \) | Boltzmann constant (\( K_B = 1.38 \cdot 10^{-23} \) J/K) |
| \( n \) | Diode ideality factor |
| \( T \) | Junction temperature in Kelvin (K) |
| \( G \) | Solar irradiation (W/m²) |
| \( \alpha \) | Junction temperature in Kelvin (K) |
| \( \nu_{dc}, \nu_{sd} \) | DC-Link voltage and current |
| \( i_{gd}, i_{sq} \) | Direct and quadratic grid voltages (V) |
| \( i_{gs}, i_{qs} \) | Direct and quadratic grid currents (A) |

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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