1 | INTRODUCTION

Due to the need for a reduction of greenhouse gas emissions such as carbon dioxide, scientists have taken on the task of finding many sources that can solve energy problems in the environmental condition. The renewable energy sources are the result of this research. Therefore, after the first big oil crisis of the 20th century, the use of renewable energy increased greatly [1]. The demand of this inexhaustible, clean and ultimate energy is continuously increasing because of economic and technical challenges. Consequently, the future sustainability depends heavily on the renewable energy problem which is addressed and the efforts in using this energy caused in single technologies.

In recent years, wind and solar energy systems are ones of the renewable energies which have been widely developed. Wind and solar resources are considered the primary alternative energy resources throughout the world. Due to seasonal, periodical and climatically variations a stand-alone hybrid (wind and solar) system can't provide a continuous supply of energy. It is prudent that a combination of wind farms and solar parks with an energy storage system (batteries) present an unbeatable option for the supply of electrical loads at remote locations [2]. However, common drawback with standalone hybrid systems is their unpredictable nature and dependence on weather and climatic changes which results difficulties in regulating the output power based in the load. So, the major limitation for hybrid systems is power management control for an optimal efficiency.

Many hybrid power systems and power management algorithms have been proposed in the literature up to now. Among them, [3] presents an experimental study of a standalone hybrid microgrid system. [4] proposes an energy management and control system for laboratory scale microgrid based on hybrid energy resources such as wind, solar, and battery. The drawbacks of the two previous papers that are focus on the power management and don’t take in consideration of the PV and wind system’s power control. [5] Proposes a hybrid energy system consisting of wind, photovoltaic and fuel cell with battery storage to supply continuous power. [6] Develops a hybrid renewable energy system: photovoltaic-fuel cell and battery which help to increase system reliability and improve power quality. A three input DC–DC boost converter is proposed for hybrid photovoltaic /fuel cell energy system for stand-alone applications is described in [7, 8, 11]. More the neglecting of MPPT controller, these works has a major disadvantage which is using the fuel cell with the wind and PV system.

Thus far, it should be remarked that the similarity in all of the above articles is that no paper has focuses in the rapidity of...
power exchange and the power quality. In fact, all used power management algorithms are implemented without considering the rapidity convergence to the MPP, the robustness under the external variations and the oscillations of the signal around the MPP. Therefore, this paper deals with the simulation and control of (PV/wind) hybrid systems including energy storage battery connected to the AC load. Many MPPT methods have been developed in the literature up to now, to increases efficiency of solar photovoltaic system and wind system. Synergetic control as a solution is proposed in this paper to ensure stability of PV and wind systems with fast dynamic response. So, the main objectives of this study are:

• Giving a robust power controller for a PV and Wind system.
• Comparing the performance of this controller with P&O for PV system and TV for Wind system
• Demonstrate the effectiveness and robustness of the used MPPT for Satisfying demanded power under different climatic and load conditions.

This paper is organized as follows. Section 2 gives a brief overview of system components that power source models, their corresponding converters, battery storage and the power management strategy (PMS) as well as the corresponding objectives and used indicators. Section 3 presents a detail description of synergetic control and its application in PV and Wind systems. The simulation results are also reported in Section 4. Finally, Section 5 summarizes the main outcome of this paper.

2 | HYBRID SYSTEM

2.1 | PV system

2.1.1 | PV panel model

PV system generates electrical power from the solar radiation. It works under the phenomenon of the photoelectric effect, when solar irradiation penetrates to the Solar Cells surface, a DC current flow through the PV panels [12, 13]. The photovoltaic cell produces around 0.5 V, and it is the smallest unit of the PV panel. PV Cells are connected in series or parallel combination to form a photovoltaic array. The single diode model is the most classical one described in literature [14]. Figure 2 illustrates the equivalent circuit model of a PV module which consists of current source, a diode, a parallel resistance and a series resistance [15, 16].

![Figure 2: Equivalent circuit of solar cell](image-url)

The output current of PV cell can be expressed as:

$$I = N_p I_{ph} - N_p I_s \left( \exp \left( \frac{q V_{pv} + R_s I_{pv}}{N_p I_s} \right) - 1 \right)$$  

Equation (1) with $R_s = 0$ and $R_{sh} = \infty$ becomes:

$$I = N_p I_{ph} - N_p I_s \left( \exp \left( \frac{A V_{pv}}{N_p I_s} \right) - 1 \right)$$  

An ideal PV cell has very high equivalent shunt resistance and very low equivalent series resistance (simplification $R_{sh} \gg R_s$).

2.1.2 | DC–DC converter

In order to extract the maximum power from the PV module, the DC–DC converter allows between the PV module and the load for boosting the photovoltaic array’s voltage and maximizing the power [17]. Figure 3 shows the circuit of the boost converter.

The boost converter can be used to drive a high voltage load from a low voltage PV module. The dynamic model of the used
2.2 | Wind system

The detailed design and complete mathematical modelling of wind system can be found in many papers [18, 19]. The wind turbine generator used in this paper employs a PMSG directly coupled to the wind turbine and connected to a three-phase inverter which rectifies the current from the generator to charge the DC-Link.

2.2.1 | Model of wind turbine

The wind turbine is used for extraction of power from wind and converters it to mechanical work. The mechanical power available from a variable speed wind turbine can be expressed as follows [20, 21]:

\[
P = \frac{1}{2} \varphi SV^3 C_p(\lambda, \beta) \tag{4}
\]

Where \( \varphi \) is the air density, \( S \) is rotor swept area, \( V \) is the wind speed and \( C_p \) is the power coefficient.

The power coefficient is a non-linear function of the blade pitch angle \( \beta \) and the speed ratio \( \lambda \) as determined by [22]:

\[
C_p = 0.5176 \left( \frac{116}{\lambda} - 0.4 \beta - 5 \right) \left( \frac{\lambda}{\lambda_i} \right)^{1/7} \tag{5}
\]

\[
\lambda_i = \left[ \frac{1}{\lambda + 0.08} \left( \frac{0.035}{\beta^3 + 1} \right) \right]^{-1} \tag{6}
\]

The ratio of tip speed (\( \lambda \)), determined as the linear speed ratio and is given by:

\[
\lambda = \frac{\omega \times R}{V} \tag{7}
\]

where, \( \omega \) is the blades angular velocity.

2.2.2 | Model of PMSG

The Permanent Magnet Synchronous Generator’s commonly used model is the Park model. Using generator convention, The PMSG model is described by the following equations:

\[
\begin{align*}
V_d &= R_s I_d + L_s \frac{dI_d}{dt} - p \omega L_s I_q \\
V_q &= R_s I_q + L_s \frac{dI_q}{dt} + p \omega L_s I_d + p \omega \psi
\end{align*} \tag{8}
\]

where, \( V_d, V_q, I_d, I_q \) are the \( d \)– and \( q \)–component of instant stator voltage and current. \( L_s \) is the leakage inductance of the stator winding, \( I_d \) and \( I_q \) are the stator and rotor \( d \)– and \( q \)–axis mutual inductances, respectively. \( R_s \) is the resistance of the stator winding, \( \omega \) is the generator electrical rotational speed and \( \psi \) is the flux linkage produced by the permanent magnet.

The electromagnetic torque can be derived from [23]:

\[
C_e = \frac{3}{2} \rho \left( I_d I_q \left( L_{dq} - L_{qd} \right) + \phi_i \right) \tag{9}
\]

The difference between the \( d \)– and \( q \)–axis mutual inductance is very small for a direct-driven multi-pole PMSG [24, 25]. Therefore, we can reduce Equation (9) to the following equation:

\[
C_e = \frac{3}{2} \rho \phi_i \tag{10}
\]

2.3 | Battery energy storage system

Energy storage systems play an important role in the power performance of Hybrid systems [26, 27]. Batteries are among the most appropriate Energy storage system for hybrid systems, for all the energy storage devices [28, 29]. There are several batteries’ types: nickel-cadmium, nickel-iron, iron-air, Lead-acid …. However, the most used batteries in hybrid systems are of deep-cycle lead-acid type, because of their reliability for practical application. The simplified model of the lead-acid battery is shown in Figure 4.

It is an ideal model with \( E_{bat}, R_{bat}, V_{bat} \) respectively representing the open circuit voltage, the equivalent internal resistance and the voltage across the terminals [30]. When the voltage \( V_{dc} \) is less than \( E_{bat} \), the current is provided by the battery \( (I_d) \). In the contrary case, the current is received \((I)\). An important parameter to represent the state of the battery is the state of charge.

\[
\begin{align*}
\frac{dV_{dc}}{dt} &= \frac{1}{C_1} (i_{pv} - i_L) \\
\frac{dI_L}{dt} &= \frac{1}{L} V_{dc} + \frac{1}{L} (S-1) V_0 \\
\frac{dV_0}{dt} &= \frac{1}{C_2} (i_L - i_0) - \frac{1}{C_2} S i_L
\end{align*} \tag{3}
\]
The state of charge of the batteries (SOC) is based on the following constraints:

\[ \text{SOC}_{\text{min}} \leq \text{SOC} \leq \text{SOC}_{\text{max}} \]  

(12)

where, \( \text{SOC}_{\text{min}} \) and \( \text{SOC}_{\text{max}} \) are the minimum and the maximum allowable states for the battery safety.

\( \text{SOC}_{\text{max}} \), given as the upper limit, is equal to the total nominal capacity of the battery bank (\( C_n \)). \( C_n \) is related to the total number (\( N_{\text{bat}} \)) of batteries, the number (\( N_{\text{bat}} \)) of batteries connected in series, and the nominal capacity of each battery (\( C_{\text{bat}} \)); then, it is given by this equation [30]:

\[ C_n = \left( \frac{N_{\text{bat}}}{N_{\text{bat}}^s} \right) C_{\text{bat}} \]  

(13)

\( \text{SOC}_{\text{min}} \) is the lower limit that the battery bank does not have exceeded at the time of discharging, which may be expressed as follows:

\[ \text{SOC}_{\text{min}} = (1 - \text{DOD}) \text{SOC}_{\text{max}} \]  

(14)

where, DOD is the depth of discharge.

2.4 Power management strategy

In this paper, a PMS for the hybrid wind/PV system is developed in order to achieve a robust, efficient, and optimal power flow. In fact, the main objectives of our PMS are satisfying the demanded power and control the power exchange between the different renewable resources and achieving the maximum utilization of renewable resources and minimum usage of batteries to extend their lifetime.

The circuit topology of the proposed PV-wind hybrid standalone system is shown in Figure 1. The proposed control strategy controls the battery state of charge by keeping the DC bus voltage constant. Battery is connected to the DC bus through a bidirectional DC/DC converters [4]. The battery control considers all possible operating conditions to run a hybrid system efficiently.

For an optimal hybrid system, \( P_{\text{sys}} \) should be equal to \( P_L \). The energy not supplied (ENS):

\[ ENS = \sum (P_L - P_{\text{GP}}) \]  

(17)

where, \( P_{\text{GP}} \) is the power generated by renewable energy resources in considering system reliability model. If ENS is zero all the time, the system cover the demanded energy of the charge. The Loss of electric Power Supply Probability (LPSP)
can be calculated by:

\[ LPSP = \frac{ENS}{\sum P_L} \]  

(18)

3 SYNERGETIC MPPT CONTROLLER

3.1 SC design procedure

SC theory was introduced in [31]. It is a state space approach for the design control for non-linear systems. We suppose that the nonlinear system is described by this differential equation [30]:

\[ \dot{x} = f(x, d, t) \]  

(19)

where, \( x \) is the state vector, \( d \) is the control input vector and \( t \) is time. This approach starts by defining the macro-variable of the state variables as follows:

\[ \psi = \psi(x, t) \]  

(20)

The control will force the system to operate the manifold \( \psi = 0 \). The designer can select the characteristics of this macro-variable according to the control specifications. In the trivial case the macro-variable can be a simple linear combination of the state variables.

The same process can be repeated, defining as many macro-variables as control channels. The desired dynamic evolution of the macro-variable is [14]:

\[ T \dot{\psi} + \psi = 0, T > 0 \]  

(21)

where, \( T \) is a design parameter specifying the convergence speed to the manifold specified by the macro-variable. The chain rule of differentiation gives:

\[ \dot{\psi} = \frac{d\psi}{dx} \dot{x} \]  

(22)

Combining Equations (20)–(22) we obtain:

\[ T \frac{d\psi}{dx} f((x, d, t)) \psi + \psi = 0 \]  

(23)

Summarizing, each manifold introduces a new constraint on the state space domain and reduces the order of the system, working in the direction of global stability. The procedure summarized here can be easily implemented as a computer program for automatic synthesis of the control law or can be performed by hand for simple systems, such as the boost converter used for this study, which has a small number of state variables.

By the suitable selection of macro-variables, the designer can obtain interesting characteristics for the final system such as:

- Global stability
- Parameter insensitivity
- Noise suppression

These results are obtained while working on the full nonlinear system and the designer does not need to introduce simplifications in the modelling process to obtain a linear description as is required for classical control theory.

3.2 Synergetic MPPT controller for PV system

MPPT is an important stage for tracking the PV system's MPP. Hence, SC's modelling is based on the output power of the PV cell \( (P = V_{pv} \times I_{pv}) \). To optimize the power, we selected the manifold as [14]:

\[ \frac{\partial P}{\partial V_{pv}} = 0 \]  

(24)

The manifold is presented as follow:

\[ \psi = \frac{\partial P}{\partial V_{pv}} = V_{pv} \frac{\partial I_{pv}}{\partial V_{pv}} + I_{pv} \]  

(25)

In studied boost, we find two states; the output voltage and the inductor current, \( \Psi \) is function of \( V_0 \) only. So, \( \Psi \) becomes:

\[ \psi = \frac{\partial \Psi}{\partial V_{pv}} V_{pv} = \left[ \frac{\partial I_{pv}}{\partial V_{pv}} + \frac{\partial^2 I_{pv}}{\partial V_{pv}^2} V_{pv} \right] V_{pv} \]  

(26)

where,

\[ \frac{\partial I_{pv}}{\partial V_{pv}} = -I_s B_v V_{pv} \]  

(27)

The macro-variable's dynamic evolution can be expressed by:

\[ T \dot{\psi} + \psi = 0, T > 0 \]  

(28)

\[ T \left[ \frac{\partial I_{pv}}{\partial V_{pv}} + \frac{\partial^2 I_{pv}}{\partial V_{pv}^2} V_{pv} \right] \dot{V} + V_{pv} \frac{\partial I_{pv}}{\partial V_{pv}} + I_{pv} = 0 \]  

(29)

\[ d = 1 - \frac{V_{pv}}{V_0} \frac{\frac{\partial I_{pv}}{\partial V_{pv}} + I_{pv}}{T \left[ 2 \frac{\partial I_{pv}}{\partial V_{pv}} + \frac{\partial^2 I_{pv}}{\partial V_{pv}^2} V_{pv} \right]} \]  

(30)

4 SYNERGETIC MPPT CONTROLLER FOR WIND ENERGY SYSTEM

The synergetic controller synthesis procedure is described in the previous paragraph. As seen, we should define the same number of macro-variables as control channels in the system. In order to find the desired control law, the first step in the design of the synergetic control is the choice of a suitable macro-variable;
in general the macro-variable could be any function (including nonlinear functions) of the state variables on the $d$–$q$ axes. In surface mounted PMSG electromagnetic torque, is dependent only on the current on the $q$-axis; whereas the machine flux is related to the current on the $d$-axis. Thus macro-variables are chosen as simple linear combinations of the state variables [31]:

$$
\begin{align*}
\psi_q &= (w - w_{ref}) + K_q (i_q - i_{qref}) \\
\psi_d &= (i_d - i_{dref}) + K_d \int_0^t (i_q - i_{qref})
\end{align*}
$$

(31)

Where the value of $k_q$ is dynamically adjusted as a function of the rotational speed error, reducing its value when the error is small; however a minimum value at zero-error must be fixed for $k_q$ in order to achieve a stable control. Where the integral term is required to eliminate the steady state error for the current on the $d$-axis; also in this case the Tustin method is used to write the integral term in discrete form and its maximum value is limited in order to avoid any possible overflow during arithmetic operations.

The control objective is to force the system to operate on the manifold $\Psi_q = \Psi_d = 0$, and the characteristics of the macro-variable are selected according to the control specifications. The dynamic evolution of the macro-variable is fixed according to the equation $T \ddot{\psi} + \dot{\psi} = 0$ where, $T > 0$ is a design parameter specifying the convergence speed to the manifold specified by the macro-variables. After some calculations, $U_q$ is given by:

$$
\begin{align*}
U_q(t) &= R_i i_q + p w (L i_d + \phi) + \frac{L}{T_q} K_q \left( i_q - i_{qref} \right) \\
&+ \frac{L}{T_q} \left( w_{ref} - w \right) + \frac{L}{T_q} K_q \left( -K_q i_q + B w + T_i \right)
\end{align*}
$$

(32)

And the control $U_d$ of the PMSG is obtained:

$$
\begin{align*}
U_d(t) &= R_i i_d + \frac{p w L_i + L}{T_d} i_d - L K_q (i_d - i_{dref}) \\
&- \frac{L}{T_d} \left( i_d - i_{dref} \right) + \frac{L}{T_d} K_q \left( -i_{qref} + B w + T_i \right)
\end{align*}
$$

(33)

5 SIMULATION ANALYSIS

Using the developed mathematical model of different components of the proposed hybrid system, detailed simulation studies are carried out using MATLAB/Simulink software to verify the validity and performance of the proposed synergetic control.

5.1 PV simulation

Various control strategies have been developed in the literature for tracking the maximum power point of PV array. The conventional P&O is the most widely used MPPT technique and the most simple and effective control. Therefore, it is considered as a standard benchmark for any new MPPT algorithm to compare. However, its major disadvantages are instability against parameter variations and chattering phenomenon. Therefore we use P&O MPPT controller for demonstrate the performance of Synergetic one under the variation of the temperature and solar radiation. Figures 6 and 8 presents respectively the irradiance and temperature profile, in which the irradiance and temperature are increased or decreased. Figure 7
simulates The PV system tracking performance with irradiation variation under the same temperature and Figure 9 simulates The PV system tracking performance with temperature variation under the same irradiation.

It is clear on the results that the two MPPT controllers are able to track the maximum power point and stabilize it under irradiation or temperature changes. However, SC is more advantageous over P&O because it is the most rapid and removes chattering problem output signal in all solar radiation and temperature variations.

5.2 | Wind simulation

The Wind system control is controlling the mechanical torque or power transmitted by the PMSG. To approve the effectiveness of the proposed approach, comparative analysis of MPPT controller built using torque vector.

Vector control considers torque as a reference input which uses PI controllers. Then, the torque control is converted to stator q-axis current control, while the stator d-axis current is set to zero. Figures 10 and 11 give the wind speed profile and wind output power respectively.

The simulation results show that SC is more advantage over torque vector because it is most robust to obtain an optimal wind system.

5.3 | Hybrid simulation

In order to verify the performance of the hybrid system, simulation studies have been carried out using different load demand data and weather data. Figures 12, 13 and 14 show respectively power load, solar radiation and wind speed.
The system is designed to supply load power and maintain the power management objectives defined previously under dynamic conditions. So, Figure 15 shows the power of PV generator, wind generator, battery bank and Load. As seen, under different condition the used hybrid system can cover the load power rapidly and without chattering that demonstrates the performance of the proposed MPPT controller.

From Figure 16, it is clear that DC-link voltage is constant at a value of 600 V. Figures 17, 18 and 19 simulates respectively the power of the hybrid system which is compared with load power, ENS and LPSP.

Despite variations in climatic condition and load power, all the simulation results demonstrate the reliability and the robustness of the used power control. So, synergetic control is used to eliminates oscillations and enhance the rapidity of system.

6 | CONCLUSION

In this paper, a synergetic control is employed to extract the maximum power tracking for both PV and wind systems and to
deliver these maximum powers to a fixed DC voltage bus. The performance of the proposed control was evaluated by using a dynamic evaluation of the wind, solar and load variable potential. The results of this paper demonstrate that using SC controllers for tracking the maximum power in both wind and PV energy systems is robust, rapid and no oscillation problem under the external variations.

Therefore, the proposed model can be considered as an initial part of building prototype of stand-alone PV-wind hybrid system.

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