Power management and DC link voltage regulation in renewable energy system

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Abstract—This paper presents a control of a stand-alone-hybrid wind solar energy system with battery storage. The system is composed essentially of wind turbine, photovoltaic panels, a storage battery unit and three phase AC load. Electronic converters play a very important role in order to connecting different sources with DC main bus for feeding a three-phase load. The objectives envisioned by this study is the continuity of load supplying and the coordination between the different sources of the system. The wind turbine and solar panel are monitored to run under maximum power point tracking MPPT controller in order to extract the available power from the wind and solar sources. A speed controller and a single input fuzzy logic controller SIFLC are used respectively. An energy management system based on the battery state of charge is developed and implemented through matlab-simulink to ensure the continuity of load supply. The line to line AC output voltage regulation based on PID controller to supply RL load with constant amplitude and frequency has been achieved.

Keywords—energy management, Wind energy, solar energy, conversion, storage, hybrid system, control, Fuzzy control, Maximum power point trackers.

I. INTRODUCTION

Solar energy, and wind energy, are the most exploited renewable energy resources. According to ‘Renewables Global Status report (2018) (REN21)’, wind power can be considered as a lead source of a new capacity generating power in USA and Europe during the year 2017, and the second largest power resource in China. Globally, a wind power capacity of 52 GW was added for a total of around 487 GW. Based on the reliability and low cost production of wind energy, many corporations and private companies are increasingly turning to this kind of power source, and many large investors were drawn by its stable incomes [1]. The top source of a new power capacity in 2017 was the solar PV in several markets such as India, Japan, United States, and China. Worldwide, and at least 98 GW of solar PV capacity was installed (on- and off-grid), increasing total capacity by nearly one-third, for a cumulative total of approximately 402 GW on average [1].

The need for Energy Management Strategy for a HES strongly arises to monitor the energy flow through the power system. This need is not only for the HES in isolated sites, but it is also important for the HES connected to electrical networks. Several tasks are ensured by this management strategy, among them, the continuity of supplying loads in all conditions, maximizing the use of renewable energy sources, protecting equipment against overloads, integrating with power generation cost optimization methods, and increasing the stability in the energy system. Furthermore, the role of management strategies in the HES connected to power grids is the control of power flow to and from networks and other counting purposes. The HES disconnection at peak load moments and the operation in periods characterized by reduced cost are also among the objectives of management strategies [2].

Several management strategies were proposed in literature such as, for stand-alone HES in [3] to address the intermittency problem; authors tested the performances of three management strategies of HES in isolated site comprising PV / wind / PEMFC, where the PV and wind are used as primary sources, and PEMFC is used as a secondary or backup source. The strategies serve to increase the fuel cell membrane and ensure power flow from the HES to the load. In [4] the authors evaluated the performance of two management strategies in which they used hysteresis band in their process; the HES which includes PV, wind and a storage system based on hydrogen for a period of more than four months. Hysteresis band provided a very great flexibility for FC, electrolyzer, and battery operations, and decreased the number of start-ups-shutdowns of storage sources [2].

On the other hand, for HES connected to electrical networks, authors in [5] proposed a consumer-side power management model to integrate it with the counting system. In this model, a pre-processed counting system was implemented and introduced with control function that acted on consumer demand. This model serves to restrict the consumers to be proprietary with the availability of renewable energy on a monthly basis. In [6] authors proposed a PV system connected to the electrical network for feeding a DC load from this electrical network without breaking Any surplus of power can be injected into the electrical network with a high quality. The battery voltage was controlled, and the signals which indicate the state of charge or deeper discharge of the battery are generated [2], to select the operating mode of the bidirectional converter (buck or boost).
In this paper, to handle the problem of power flow management in standalone HES, a monitoring system was proposed and verified through matlab-simulink based on batteries state of charge. This paper is organized as follows: section 2 presents a description and modelling of the different parts of a Hybrid Energy System. The details of the management strategy of HES proposed in this paper are demonstrated in section 3. Then, the obtained results and discussions are provided in section 4. The conclusions and future works are summarized in section 5.

II. DESCRIPTION AND MODELLING OF A HYBRID ENERGY SYSTEM

This study deals with a hybrid system with three renewable energy sources: wind turbine (WT), photovoltaic (PV) panels and storage batteries. WT and PV panels are used as primary energy sources, while storage batteries are used as a secondary or backup energy sources. The system studied here consists of a wind generator of 5 kW, and a PV generator of 5 kW. The general scheme of a hybrid system can be represented by Figure 1.

![Figure 1: Overall Hybrid Energy System structure](image)

a- The studied system can be divided into four parts:
- The WT generator side consists PMSG, uncontrolled bridge diode and buck DC-DC converter.
- The PV generator side contains PV modules and DC-DC buck converter for MPPT.
- The load side involves the three-phase-inverter, LC filter, and RL load. Furthermore, a dump load is used to protect the batteries from overcharging.
- The energy storage side contains a buck-boost DC-DC converter with lead acid battery.

The DC link voltage is depending of WT, PV generators power output and the load impedance [7]. Therefore, in this study, the authors used Fractional order PID control approach of DC-link voltage to overcome the unstable voltage supply [7][8] based on the buck-boost DC-DC converter[10]. The DC-AC converter was controlled using the line to line output voltage control based on PID controller.

A. Wind generator Modelling

The wind generator used in this study is made up mainly of a wind turbine, a permanent magnet synchronous generator (PMSG), an uncontrolled rectifier and a Boost converter. The model of each component are presented as follows:

1) Wind turbine:

The amount of aerodynamic power harvested from the wind turbine (WT), as shown in Figure 1 (a), can be expressed by the following equation:

$$ P_{aer} = C_p \cdot P \cdot V = C_p(\lambda, \beta) \frac{\rho \cdot S \cdot V^3}{2} $$

(1)

where $P_{aer}$ is the aerodynamic power (W), $\rho$ is the air density (kg/m$^3$), $V$ is the wind speed (m/s), $S$ is the swept area of the turbine (m$^2$), and $C_p$ is the power coefficient of wind speed defined as follows [10][11]:

$$ C_p(\lambda, \beta) = \begin{cases} \frac{\pi (\lambda+0.1)}{18-0.3(\lambda-2)^2} & \text{if } \lambda > 2 \\ 0 & \text{if } 1 < \lambda < 2 \\ 0.5 & \text{if } \lambda < 1 \end{cases} $$

(2)

$\beta$ is a blade pitch angle, $\lambda$ is speed ratio defined as follows:

$$ \lambda = \frac{\Omega_{t} \cdot \omega_{\phi}}{V_{wind}} $$

(3)

$\Omega_t$ is turbine speed, $V_{wind}$ is the wind speed. $R$ is the radius of turbine blades.

The relation between wind power coefficient $C_p(\lambda, \beta)$ and a tip speed ratio $\Omega$ when blade pitch-angle $\beta = 2^\circ$ is shown in Figure 2.

$$ \beta = 2^\circ $$

![Figure 2: Power coefficient Cp and tip speed ratio characteristics at a blade pitch angle under](image)

The aerodynamic torque is given by:

$$ \tau_{aer} = \frac{P_{aer}}{\Omega} = C_p \cdot \frac{\rho \cdot S \cdot V^3}{2} $$

(4)

The main objective of the Maximum Power Point Tracking (MPPT) control in wind turbine is to ensure the extraction of the maximum available power from the wind. There are different MPPT control algorithms, among them the optimal torque control based on the following equation:

$$ \tau_{opt} = C_p \cdot \frac{\rho \cdot S \cdot V^3}{2} $$

(5)

As can be noticed, the power coefficient $C_p$ is a function of $\Omega$ and $\beta$ and reaches the maximum at the particular $\lambda_{opt}$ and $\beta_{opt}$, so should be kept in this value, with the optimal rotor speed. More details of this type of MPPT control can be found in[10].

2) PMSG Dynamic Model

The dynamic model of PMSG shown in Figure 1 (a) is described in d-q coordinate rotor frame, in which the q-axis is 90° ahead of the d-axis, with respect to the direction of rotation. The stator voltage of PMSG can be written as follows [10][11]:

$$ \begin{cases} \begin{align} -R \cdot i_{ds} - L_s \cdot \frac{di_{ds}}{dt} + \omega \cdot L_s \cdot i_{qs} &= v_{ds} \\ -R \cdot i_{qs} - L_s \cdot \frac{di_{qs}}{dt} + \omega \cdot L_s \cdot i_{ds} + \omega \cdot \varphi_f &= v_{qs} \end{align} \end{cases} $$

(6)

where $v_{ds}$, $v_{qs}$: d-q axis stator voltage, $i_{ds}$, $i_{qs}$: d-q axis stator current, $L_d$, $L_q$: d-q axis inductance, $R$: stator resistance, $\omega$: electrical pulsation, $\varphi_f$: magnetic flux.

The electromagnetic torque is expressed below by:

$$ T_{es} = \frac{3}{2} P \left[ (L_s - L_d) \cdot i_{ds} \cdot i_{qs} + i_{qs} \cdot \varphi_f \right] $$

(7)

where $P$: the number of pole pairs.

After flux axes orientation, the Eq (7) becomes as follows:
The schematic of the Buck converter power stage is given in Fig. 3, as shown in Figure 1 (a). When wind speed varies with time, PMSG rotational speed also does. The produced voltage by the PMSG varies in amplitude and frequency. In this case, the voltage is unsuitable for both users and electric loads [12]. Therefore, to avoid this upset, the produced voltage is converted to DC voltage then converted to controllable AC voltage in uncontrolled 3 phase AC-DC converter Figure.3, as shown in Figure 1 (a), is used to convert the AC variable voltage of PMSG to variable DC voltage, by considering that the angles of switching and inductance are negligible.

\[
T_{dc} = \frac{\sqrt{3}}{2} P i_n \varphi / \cos \varphi = K \Delta i,
\]

3) Uncontrolled AC-DC Converter

When wind speed varies with time, PMSG rotational speed also does. Hence, the produced voltage by the PMSG varies in amplitude and frequency. In this case, the voltage is unsuitable for both users and electric loads [12]. Therefore, to avoid this upset, the produced voltage is converted to DC voltage then converted to controllable AC voltage in amplitude and frequency. In this work, an uncontrolled 3φ bridge diode rectifier Figure.3, as shown in Figure 1 (a), is used to convert the AC variable voltage of PMSG to variable DC voltage, by considering that the angles of switching and inductance are negligible.

The output Current and voltage of the AC-DC converter are as follow [10]:

\[
\begin{aligned}
U_o &= \frac{1}{\sqrt{2}} U_{g_{av}} d_{av} = \frac{1}{\sqrt{2}} \frac{\pi}{6} U_{g_{av}} \\
I_o &= \frac{\pi}{6} I_{g_{av}}
\end{aligned}
\]

where \(U_o\) and \(I_o\) are the average output current and voltage values of the AC-DC converter, \(U_{g_{av}}\) and \(I_{g_{av}}\) are the effective voltage and current values of the alternative side.

4) DC-DC Buck Converter

The DC-DC buck converter, as shown in Figure 1 (a), plays a significant role in the whole WT system; it behaves as an interface between the bridge diode converter and the DC bus. It is used to ensure the extraction of the maximum available electric power from the wind energy. The schematic of the Buck converter power stage is given in the following Figure [13]:

![Fig. 4. DC-DC Buck converter model](image)

The dynamic model can be expressed by the following equations:

\[
\begin{aligned}
\dot{V}_P &= L \frac{d i_1}{dt} + i_1 R_{d1} + V_o \\
\dot{i}_1 &= \frac{1}{L} (V_p - i_1 R_{d1} + V_o) dt
\end{aligned}
\]

where \(V_{in}\): Input Voltage of the Buck Converter. D =1 when Duty Cycle is ON and D =0 when Duty Cycle is OFF.

\(I_{d1}\) : Inductor Current \(R_{d1}\) : Effective Series Resistance of Inductance \(V_{out}\) : output Voltage of the Buck converter \(L\) : Inductance Value in Henry

B. PV generator model

Various variants of modeled PV exist in the literature, including the electrical model of the photovoltaic generator with two diodes as illustrated in Figure 5.

![Fig. 5. Equivalent electrical diagram of the two-diode model of a PV cell.](image)

for modeling the incident solar irradiation (Fig.5), a current source \(I_{ph}\) is used. The diodes \(d_1\) and \(d_2\) represent the polarization phenomenon whereas the power losses are respectively represented by a series and parallel resistors \(R_1\) (s) and \(R_2\) (p). The mathematical equation that describes the PV panel consisting of 36 cells connected in series is given by:

\[
I = I_{ph} - I_{ph1} \left[ \exp \left( \frac{(V + I_{ph1} R_1)}{N_{sc} q T} \right) - 1 \right] - I_{ph2} \left[ \exp \left( \frac{(V + I_{ph2} R_2)}{N_{sc} q T} \right) - 1 \right]
\]

1) MPPT for PV system

The PV system used in this study was operated under maximum power point tracking-MPPT- to extract the maximum available power from the panels, based a single input fuzzy logic controller. The latter uses error E as input and change in duty ratio \(DD\) as output. More details can be found in [14].

Taking \(E = (\Delta P/\Delta V)\), for each step and by considering the sign of \(\Delta P\) and \(\Delta V\), we conclude that:

\[
\begin{aligned}
& \text{IF} \ E < 0 \text{ then } D = D + \Delta D \\
& \text{IF} \ E > 0 \text{ then } D = D - \Delta D \\
& \text{IF} \ E = 0 \text{ then } D = D
\end{aligned}
\]

C. Energy storage system (ESS) model

To maintain the DC bus voltage at a desired fixed value, a lead-acid battery and DC-DC a bidirectional buck boost converter were used. A simplified model of this battery is presented in figure 7:

![Fig. 6. Block diagram of a photovoltaic system with SIFLC-MPPT technique.](image)
PSO algorithm is used for tuning FLC parameters ($\phi,k,r$)

\[ \text{Eq. 15:} \]

\[ V_{\text{bat}} = \frac{E_0 - iR_{\text{in}} - k}{Q - Q_{\text{act}}} + A \frac{Q - Q_{\text{act}}}{Q} \]  

where:

- $E_0$: Initial voltage
- $R_{\text{in}}$: Internal resistance
- $i$: Battery current
- $Q_{\text{act}}$: Current battery capacity

This model calculates the voltage across the battery, its state of charge (SOC) and losses. It is assumed that the losses are purely ohmic. To simplify the calculation, we put:

\[ V_{\text{bat}} = E_0 - iR_{\text{in}} \]  

The battery state of charge (SOC) can be assessed using the following expression [18]:

\[ \text{SOC} = 100 \left( 1 + \frac{j1dt}{Q} \right) \]  

The battery charge-discharge depends on the available power, the demand and the SOC [18]. The energy constraints of the battery are determined based on the SOC limits:

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

The DC-link voltage is controlled in the ESS through a FOPID control strategy as shown in Fig. 8.

D. DC-AC Inverter Control

In this study, the DC-AC inverter depicted in Figure 9 is used to feed the load with a certain constant voltage in amplitude and frequency.

\[ \text{Eq. 16:} \]

\[ V_{\text{bus}} = f_1(S_1,S_4) + f_2(S_2,S_5) + f_3(S_3,S_6) \]

\[ \text{Eq. 17:} \]

\[ f_i = \frac{1}{3} V_{\text{bus}} \]  

If $i_a, i_b, i_c$ are the currents of the alternative part, the current in the continuous part can be obtained from the power conservation law. Using the expression ($P=V_{\text{bus}}i_{\text{bus}}$):

where $f_1, f_2, f_3$ are the switches states (on, off).

To control the line to line load voltage, the authors apply voltage-fed control strategy. For more details check references [9][16][17].

III. HYBRID ENERGY SYSTEM MANAGEMENT POWER

To manage the electrical energy generated by the hybrid system (Fig.1), we need a supervisor, who must optimize the use of the produced energy and that of the battery. If renewable sources do not provide enough power and the battery capacity is sufficient, which means that the SOC is greater than the minimum value, the battery will provide the missing power (Fig.10). Else load shedding is compulsory to keep power balance as the power supply is less than demand and the battery is at its minimum capacity (Fig.11). For this system it is assumed that the battery is fully charged initially. On the other hand, if the hybrid power exceeds the demand of the load, the surplus will be stored in the battery and if this one is full (SOC=SOC_{max}), the surplus will be dissipated in a dump load (here is the resistance). Thus, the battery is not the main supplier, its charge / discharge rate is reduced, and thus the battery life is extended, based on current commands of the various converters and on the estimation of the state of charge of the batteries. Energy management strategy flowchart implemented in this study can be presented as follow:

\[ \text{Eq. 18:} \]

\[ V = E_0 - iR_{\text{in}} \]  

We assume that the state of charge of the battery is 85% (almost full) to be able to check all operation cases. The requested power ($P_{\text{demd}}$), wind speed and irradiation are variable to test the operation of the controllers proposed under various climatic conditions.

- For $t \in [0 \text{ s}, 3 \text{ s}]$ (Fig.11.a), the requested power ($P_{\text{demd}}$) is equal to $\approx 1400 \text{ W}$. It is provided by the GPV since in this interval it produces $\approx 3360 \text{ W}$.
- For $t \in [3 \text{ s}, 6 \text{ s}]$ (Fig.11.a) the requested power becomes $\approx 4700 \text{ W}$, which is not possible to ensure by the two renewable sources (PV and wind). The shortage power $P_{\text{net}} = 1550 \text{ W}$ is provided by the batteries that are in discharge mode (Fig.11.g).
Fig. 11. Simulation results of HES management power
At instant 5s, the wind turbine produces a power of 4300w (Fig. 11.e) which makes it possible to satisfy the demand of power and to charge the batteries at the same time. at 7.5 seconds a drop of P_dem almost zero (Fig. 11.a), the surplus becomes too big, which gives the possibility to continue charging the batteries.

At instant 13.6s (Fig. 11.i), the state of charge (SOC) of the batteries reaches its maximum (90%). To prevent the battery from leaking, a dump load is activated (S1 = 1) (Fig. 11.i) to dissipate excess power.

Figure 11.j shows the waveform of the DC bus voltage which is kept constant over the entire operating range. These simulations show that our controller offers good results. It ensures load demand despite the variations in weather conditions, with good power while respecting the charging process of the battery.

V. CONCLUSION

Energy management control of a hybrid wind PV with battery storage has been proposed in this paper to meet a load request regardless of the renewable sources intermittence and impedance load variation. MPPT controller for wind and solar based on speed tracking and SPIPLC respectively have been presented to extract available aerodynamic and solar power. The line to line AC output voltage regulation based on PID controller to supply RL load with constant amplitude and frequency has been achieved. The effectiveness of the proposed controls was tested via matlab-simulink, the obtained results demonstrate the performance of the system and are highly promising for future works.

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APPENDIX A

- PVG SIMULINK MODEL PARAMETERS:

| Equivalent resistance in series R_s (Ω) | 15 mΩ |
| Equivalent resistance in parallel R_p (Ω) | 30 Ω |
| Number of cells connected in series N_s | 36 |
| Number of cells connected in parallel N_p | 1 |
| Ideality factor of diode α | 1.2 |

- DC-DC converter parameters: L=3.5 mH C1=C2=5.6 mF.
- PSO algorithm parameters: c1=c2=2.05.

-PVG EMULATOR PARAMETERS

| Short circuit current (A) | 3 |
| Current at MPPT (A) | 2.57 |
| Open circuit voltage (V) | 50 |
| Voltage at MPPT (V) | 45.93 |
| Power of MPP (W) | 1137 |

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