A Hybrid Wind-Solar-Storage Energy Generation System Configuration and Control

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Abstract—This paper proposes a standalone distributed hybrid power system which consists of solar power, wind power, battery storage and the load. A control strategy is introduced to maximize the simultaneous energy harvesting from both renewable sources. The controller results in five contingencies considering the level of power generation available at each renewable energy source and the state of charge in the battery. Power converters interface the source with a common DC bus. The interfacing converter is controlled either as a current or a voltage source. A supervisory controller is proposed to accomplish the source type allocations and balance of energy in the operating contingencies. Simulation results demonstrate accurate operation of the supervisory controller and functionality of the maximum power point tracking algorithm in each operating condition both for solar and for wind power.

I. INTRODUCTION

Compared with other renewables, wind and solar have been established as proven future sources of energy, because of their environment-friendly, safe and cost-effective characteristics. However, there are some difficulties associated with combined utilization of solar and wind, e.g. intermittency of wind and instability of the grid\cite{1}. For this purpose, advanced network of multiple renewable energy systems with storage units have been proposed \cite{2},\cite{3}. Small-scale standalone combination of solar, wind and battery has been found effective in remote areas\cite{4}. Simultaneous intermittency of wind and solar can be compensated by use of energy storage devices\cite{5}. Several designs have used a power converter interface in the battery connection to control the charge-discharge process of the battery. However, a battery can be directly connected to the DC bus and be controlled by limited variation of DC bus voltage. The power converters interfacing the wind and solar can inject the power as a current source or voltage source. Supervisory controller determines the source type according to the availability and rating of the power. As the DC bus voltage floats, the battery can be charged or discharged. A designated voltage source (either wind or solar) will be controlled to charge the battery as the desired rate. When both sources are controlled to inject current, the bus voltage is determined by the battery terminals. Thus, the strategy of the supervisory controller is to satisfy the power required by the load and manage the state of battery. This new hybrid system improves the stability and reliability of power supply \cite{6},\cite{7},\cite{8}. Maximum power point tracking is continuously operated to maximize the power from wind and solar. In this paper, the perturb and observe P\&O method is used on both the solar and wind power sources \cite{9},\cite{10}.

This paper is organized as follows: Proposed hybrid energy generation unit are given in section II. The MPPT for Solar system and wind energy system are introduced in Section III. Section IV describes supervisory control strategy. Section VI represents some simulation results.

II. HYBRID ENERGY GENERATION UNIT

Fig.1 depicts the proposed topology of combined power sources consisting of solar, wind and battery with two stage DC-DC converters to interface the load. There are two main branches in the system, thus two new energy sources can compensate each other to some extent under different climates. The first stage converters are controlled by MPPT controller and capture the maximum power from wind and solar respectively. The second stage converters are controlled by local controller as a constant voltage sources (CV). The control action as voltage source is determined by the supervisory controller. Each power system branch runs a maximum-power-point tracking (MPPT) algorithm and receives the voltage and current references from the supervisory controller.

Both energy sources are connected in parallel to a common dc bus through their individual dc-dc converters. The load and battery are directly connected to dc bus. CV controller creates a controlled voltage source \cite{11},\cite{12},\cite{13} to inject current to the system and maintain the voltage.

![Fig. 1. Proposed hybrid energy generation system](image)

III. MPPT FOR SOLAR AND WIND POWER SYSTEM

To make the high cost of solar power, constant search for maximum power point generation is necessary. Maximum power point tracking is a mechanism to set the voltage output

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of the solar-connected converter to maximize the energy generation. However, as the system under MPPT is controlled as a voltage source, the set voltage reference of solar source may become different that of the source set as voltage source. The supervisory controller may override the MPPT algorithm to guarantee the stability of voltage at the DC bus. In this case, the energy generation from the solar panel is deviated from maximum power point rendering achievement of a sub-optimal solution. A PV module has been modeled in Matlab/Simulink. The simulation parameters setting of PV panel are listed in Table I.

<table>
<thead>
<tr>
<th>TABLE I. THE SIMULATION PARAMETERS SETTING OF PV PANEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{oc}$</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>129V</td>
</tr>
</tbody>
</table>

In the table, $V_{oc}$ is the open circuit voltage, $I_{sc}$ is the short circuit current, $V_{mp}$ and $I_{mp}$ are the nominal voltage and currents. $P_{mp}$ is the nominal power, $R_s$ is the series resistance of the cell, $T_{ref}$ is the reference temperature and $R_{ref}$ is the radiation at the panel. Figures 2 shows the ($P$-$V$) curves of the PV model at different solar illumination intensity levels.

As Figure 2 shows, there is a strong nonlinear relationship in the P-V curve. The output power has only one maximum power point (MPP) under every specific solar radiation. In the Figure 3, the MPP can be captured by tuning the controller and regulating the converter. Thus, the solar MPPT will be achieved through adjusting load resistance as close as possible to internal resistance of power source.

![Fig. 2. P-V characteristics of PV model.](image)

![Fig. 3. Basic diagram of solar MPDC converter.](image)

Figure 4 demonstrates the algorithm of the solar P&O method[14], [15].

![Fig. 4. Flow chart of solar MPPT algorithm.](image)

Simulations of PV MPPT profile for a 30Ω load when the temperature is 25℃ has been shown in Figure 5. Figure 5.a depicts the variation of perturbation signal during the irradiance changing from 600W/m² to 1000W/m² and then come back to 600W/m², which oscillates slightly around the best duty ratio when the radiation changes quickly. As the Figure 5.b shows, the maximum power points of PV model are approximately 1010W, 1400W and 1800W when the solar radiances are 600W/m², 800W/m² and 1000W/m² respectively.

![Fig. 5. PV MPPT Profile to step change in the irradiance from 600W/m² to 1000W/m².](image)

- a. Perturbation signal.
- b. MPPT tracking effect.
At the wind energy system, a typical wind generation system consists of wind turbine and dc generator, the wind turbine converts wind energy into mechanical energy and then the generator converts the mechanical energy into electric energy. The fundamental equation of the relationship between wind turbine output power and wind speed is given by:

$$P = \frac{1}{2} \rho AV^3 C_p$$,  

where, $\rho = 1.025 \text{kg/m}^3$ is air density ($\text{kg/m}^3$), $A$ is the area swept by rotor blades, $V$ is the velocity of air (m/sec), $C_p$ is the power coefficient of wind turbine. The tip speed ratio $\lambda$ and $C_p$ can be expressed as follows:

$$\lambda = \frac{nR}{V},$$  

$$C_p(\lambda, \beta) = C_1 \left( \frac{C_2}{\lambda_1} - C_3 \beta - C_4 \right) e^{-C_5 \lambda} + C_6 \lambda,$$  

$$\frac{1}{\lambda_1} = \frac{1}{\lambda + 0.08 \beta} - 0.035 \beta^2 + 1.$$

In the above formula, $\omega$ is the rotor speed of wind turbine (rad/s), $n$ is the rotational speed of wind turbine (r/s), $R$ is the radius of wind turbine ($R=2.5m$ in this paper), from the help information in Matlab [14-15], $C_1=0.5176$, $C_2=116$, $C_3=0.4$, $C_4=5$, $C_5=21$, $C_6=0.0068$.

The proposed wind power system in this paper consists of a fixed pitch angle 0° and variable speed wind turbine, a permanent magnet synchronous generator (PMSG) and a diode bridge rectifier was used to convert the power to DC. The wind turbine and PMSG connect directly without gearbox so the wind turbine torque and rotor speed are equal to the generator torque and rotor speed. Figure 6 shows the characteristics of the wind turbine power vs. rotor speed. From Figure 6 the maximum power under different wind speed is produced at different rotor speeds. Thus, the key point of tracking the MPP for wind turbine is to capture the optimal rotor speed for every wind speed.

\[\Delta W_T \text{ and } \Delta P_T \text{, } \Delta W_B \text{ are observed [18]-[19] similar to a voltage change command and observance of power variation.}\]

![Image](image72x290 to 78x314)  
Fig. 7. P&O method of wind system. (a) Turbine power versus shaft speed and principle of P&O method. (b) Block diagram of the P&O control in wind.

According to the principle of conservation of energy the P&O method for wind MPPT can be accomplished by tuning the duty cycle of the SEPIC converter to change the rotor speed and keep the maximum $C_p$. Figure 8 demonstrates the variation of rotor speed when tuning the duty cycle.

![Image](image81x351 to 96x343)  
Fig. 8. Configuration of proposed hybrid new energy system.

As can be seen in Figure 9, assuming the wind speed is constant, the MPPT control for wind system can also be categorized into four circumstances:

![Image](image311x288 to 544x389)  
Fig. 9. MPPT strategy for wind power system.
1. \( P_k > P_{k-1} \) and \( \omega_k > \omega_{k-1} \), the output power at \( k \) moment is larger than that of \( k-1 \) moment, so the operating point is at the left side of MPP. \( \omega_k > \omega_{k-1} \) means that the rotor speed increases, so the last duty cycle perturbation is negative. This causes that the next perturbation become positive;

2. \( P_k < P_{k-1} \) and \( \omega_k < \omega_{k-1} \), the output power at \( k \) moment is less than that of \( k-1 \) moment, so the operating point is at the left side of MPP. \( \omega_k < \omega_{k-1} \) means that rotor speed decreases, so the last duty cycle perturbation is positive. This causes that the next perturbation to become negative;

3. \( P_k > P_{k-1} \) and \( \omega_k < \omega_{k-1} \), the output power at \( k \) moment is larger than that of \( k-1 \) moment, so the operating point is at the right side of MPP. \( \omega_k < \omega_{k-1} \) means that rotor speed decreases, so the last duty cycle perturbation is negative. This causes that the next perturbation become positive;

4. \( P_k < P_{k-1} \) and \( \omega_k > \omega_{k-1} \), the output power at \( k \) moment is less than that of \( k-1 \) moment, so the operating point is at the right side of MPP. \( \omega_k > \omega_{k-1} \) means that rotor speed increases, so the last duty cycle perturbation is negative. This causes that the next perturbation to become positive.

Simulations of wind MPPT profile for a 30Ω load with wind speed variation from 4m/s to 12m/s are illustrated in Figures 10 and 11. Figures 10 and 11 depict the wind power generated directly from wind turbine and the actual power captured at the load.

![Wind MPPT tracking profile](image)

Fig. 10. Wind MPPT tracking profile to step change in the wind speed from 4m/s to 8m/s.

![Wind MPPT tracking profile](image)

Fig. 11. Wind MPPT tracking profile to step change in the wind speed from 8m/s to 12m/s.

IV. SUPERVISORY CONTROL STRATEGY

In a DC-system fed by multiple converters on a common bus, current must be shared among all sources according to their available power while ensuring the stability of the bus voltage. Therefore, a supervisory control is designed to set the voltage of DC bus and manage the power among sources and storage devices. Considering the wind, solar and a storage system feeding a common load, several contingencies may occur which are listed in Table II. Since the battery storage is directly connected to the DC bus, the supervisory controller can charge or discharge it by setting the DC bus voltage slightly higher or lower than the battery terminal voltage. To charge the battery, the converter of another source such as wind or solar must be controlled as a voltage source while the other is controlled as a current source. This decision is based on the amount of power each source is instantaneously generating. When the battery is fully charged and is required to feed the load, the battery maintains the voltage while other converters are controlled as a current source. A smooth transition from voltage to current source by the use of local controllers results in high performance and efficient controls [20, 21]. The net power that battery needs to provide, \( \Delta P \), can be obtained from the renewable energy and load power deficit as follows:

\[
\Delta P = P_s + P_w - P_{load},
\]

where \( P_s \) is the output power of solar, \( P_w \) is the output power of wind, \( P_{load} \) is the power demand from load. The supervision mode is shown in Table II which can be stated as follow: If \( \Delta P \) is greater than zero and SOC is not higher than 90\%, then no MPPT control on both wind and solar system will be required; When \( \Delta P \) is zero, battery should be disconnected as a backup power and no MPPT control on both wind and solar system will be required; In case \( \Delta P \) is less than zero and SOC is higher than 40\%, battery will be discharged to satisfy the load power demand; In the worst case, i.e. \( \Delta P \) is less than zero and SOC is lower than 40\%, the load can be disconnected and the available energy is used to charge the battery. In extreme weather conditions, a dump load is required to consume the extra power generated form the sources.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Condition</th>
<th>Control Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( \Delta P &gt; 0, \text{SOC} &lt; 90% )</td>
<td>Charge battery, Feeding Load</td>
</tr>
<tr>
<td>2</td>
<td>( \Delta P &gt; 0, \text{SOC} &gt; 90% )</td>
<td>Feeding Load, OFF Battery (No MPPT)</td>
</tr>
<tr>
<td>3</td>
<td>( \Delta P = 0 )</td>
<td>Feeding Load, OFF Battery (No MPPT)</td>
</tr>
<tr>
<td>4</td>
<td>( \Delta P &lt; 0, \text{SOC} &gt; 40% )</td>
<td>Battery discharge to satisfy the load, OFF wind and solar</td>
</tr>
<tr>
<td>5</td>
<td>( \Delta P &lt; 0, \text{SOC} &lt; 40% )</td>
<td>OFF Load, Just charge Battery</td>
</tr>
</tbody>
</table>

Table II. Contingencies in supervisory control of hybrid wind-solar-battery energy generation system.
V. SIMULATION RESULTS

A. Control for cascaded boost converter in solar system

As can be seen in Figure 1, the configuration of two stage boost converter has been accomplished in solar system. The first stage converter is operated by solar MPPT controller and captures the maximum power delivered from solar panel under different illumination intensities. The second stage converter is regulated through an adaptive voltage controller which is designed for fixed voltage control at the output of solar subsystem. The simulation results that demonstrate the solar MPPT and voltage control for a 30 \( \Omega \) load are shown in Figure 12. Fig. 12(a) depicts the solar system running at maximum power point tracking mode when the solar irradiance is 1100W/m\(^2\). The output voltage tracking was shown in Fig. 12(b), with the step change in reference voltage from 240V to 220V, the output voltage is tracked and fixed at the required voltage level.

![Control for cascaded boost converter in solar system](image.png)

(b) Output voltage tracking.

Fig. 12. Control for cascaded boost converter

B. Control for cascaded converter in wind system

Similar to solar system, the wind system consists of two stage converters. The first stage SEPIC converter works for the maximum power tracking by using the wind MPPT controller and the second stage boost converter is also regulated by an adaptive voltage controller to realize the output voltage control in the wind subsystem.

With the pitch angle 0 degree and output resistor is 30 \( \Omega \), the power coefficient of wind turbine and voltage control of wind system when wind speed is 7m/s are illustrated in Figure 13. In this case, \( C_p \) is always fixed at the maximum value 0.48 and the output voltage can also be controlled around 240V as required by battery.

![Control for cascaded converter in wind system](image.png)

(b) Output voltage control around 240V

Fig. 13. Control for cascaded converter in wind system.

C. Control for combined system

Some simulation results which reflect the MPPT performance of combined system are also demonstrated in Figure 14.

![Control for combined system](image.png)

(a) MPPT Tracking profile for combined system (OFF battery).

(b) SOC (battery discharge).

(c) Battery discharge to satisfy the load.
and applicability of the proposed method. Simulation results demonstrated an accurate operation at the common coupling point. A robust and smooth switching from renewable energy sources and battery while connected to a grid connected PV system were built in Matlab/Simulink. The P&O method was utilized in both controllers and supervisory controller were built in Matlab/Simulink. Models of a horizontal axis wind turbine and a PV array and their MPPT power tracking controllers and adaptive voltage controllers and supervisory controller were built in Matlab/Simulink. The R&O method was utilized in both wind power and solar power, which demonstrated a stable and effective tracking performance under the variation of wind speed and solar illumination. A supervisory control strategy was proposed to generate the maximum power from these renewable energy sources and battery while connected to a common coupling point. A robust and smooth switching from MPPT to power tracking mode was obtained in both power sources. Simulation results demonstrated an accurate operation and applicability of the proposed method.

VI. CONCLUSION

This paper was focused on the configuration of wind turbine and solar panel and MPPT control methods for a combined wind-solar-battery power generation system. Models of a horizontal axis wind turbine and a PV array and their MPPT power tracking controllers and adaptive voltage controllers and supervisory controller were built in Matlab/Simulink. The R&O method was utilized in both wind power and solar power, which demonstrated a stable and effective tracking performance under the variation of wind speed and solar illumination. A supervisory control strategy was proposed to generate the maximum power from these renewable energy sources and battery while connected to a common coupling point. A robust and smooth switching from MPPT to power tracking mode was obtained in both power sources. Simulation results demonstrated an accurate operation and applicability of the proposed method.

REFERENCES


