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Design of PV/Wind Hybrid System with Improved Control Strategy for Rural Area: Case Study of Sandakan, Malaysia

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Abstract

Many villagers in East Malaysia are still depending on diesel generator as their electric source. Due to the high transportation fees for the diesel, the cost to operate the diesel generator are more expensive compared to the market price in urban areas. Hybrid renewable energy systems are being implemented in the rural areas to replace the diesel generators. The hybrid system will not only reduce the cost of power, but the carbon dioxide emission as well. In this paper, an AC bus off-grid Pv/Wind hybrid system is designed using PSCAD to be used for rural electrification. This project designed a solar-wind-battery hybrid renewable energy system with a capacity of 13kW and 3kW for solar and wind respectively. The design includes an improved control strategy that does not require any dump load. The off grid hybrid system is designed and simulated for a typical load of 20 houses in Sandakan. Sandakan was selected as it has the required wind speed for wind energy. The simulation results clearly indicate that the proposed controller is able to regulate the voltage and frequency within limits for various environmental and load conditions.

Keywords: Hybrid System, Rural Electrification, Solar, Wind, Battery, Control Strategy

1. Introduction

Most of the rural areas in East Malaysia are still dependent on diesel generator to generate electricity. Over the past few years, the implementation of hybrid solar-diesel system have been increasing. Currently, hybrid system with more renewable energy sources, such as the solar-wind hybrid system, is trying to replace the hybrid solar-diesel system. Solar-wind hybrid system operates using renewable energy sources without using diesel generator. However, the solar-wind hybrid system is less popular in Malaysia where the wind energy is weak in comparison with other countries.

This paper proposes an AC coupled islanded hybrid system which consists of solar PV, wind turbine and battery storage. The design of the hybrid system utilized an improved control strategy whereby no dump load is used and the switching of the inverters are controlled based on the demand. The designed system is simulated in PSCAD and the system is tested for a load of 20 houses in Sandakan. Sandakan is chosen for the location of the case study as it has the required wind speed for wind energy. The annual average wind speed of Sandakan is 2.3m/s and the annual wind energy is 20.4kmh/m². The designed simulation is carried out for different climate condition to verify the performance of the system and to ensure the voltage and frequency of the AC bus is not violated.

Section II of this paper discusses about the load specification of 20 rural houses in Sandakan. Section III describes the design and topology of proposed hybrid system. Section IV discusses the control strategy implemented in the hybrid system. Section V shows the performance results of the proposed hybrid system in PSCAD. Lastly, section VI presents the conclusion of the paper.
2. Load Specification

This system was designed for a rural area in Sandakan which has 20 houses. The home appliances used in the house and time period of usage is shown in Table 1.

Based on Table 1, the total power consumption per day for each house was assumed to be 69kWh. Thus, the total power consumption for 20 houses was assumed to be 138.4kWh. The loading is noted to be higher during lunch time and at night when the occupants are home.

2.1 Solar Wind Hybrid System

The solar wind hybrid system is designed based on the topology in Figure 1. The three phase voltage is rated at 400V and the frequency is 50 Hz. This topology is chosen for this system as it is more reliable, economical and have a higher system efficiency. Besides that, if any one of the inverter is not functioning, the hybrid system is able to supply power from the remaining renewable energy sources to the load.

2.2 System configuration and modeling

The proposed hybrid power system is shown in Figure 1 where each renewable energy source have its own inverter which connects directly to the AC bus line. For this paper, the solar PV rating is 13.43 kW peak (11 of 305 W PV module connected in series and 4 cell string connected in parallel), wind system is rated at 3 kW and battery storage has rating of 279 kWh, 372 V (31 of 12V, 50Ah lead-acid battery connected in series and 15 cell string connected in parallel). The solar and wind power is sufficient to supply the load demand with the combination of battery.

3. Control Strategies

The solar wind hybrid system in this paper utilizes a master-slave control strategy in its inverters. To ensure the voltage and frequency at the AC bus is regulated within the range, the VF control is implemented in the battery to regulate the frequency and voltage. PQ control is the implemented in the solar and wind inverter to control the power produced. Due to the limitation of wind energy in Sandakan, the curtailment of real power is only imple-
mented in the solar inverter when the battery is fully charged. The detailed control strategies are stated as follows.

### 3.1 PQ Control

The proposed PQ control in Figure 2 is implemented in the solar and wind inverter to control the exact amount of power. Firstly, the 3-phase voltage and current are measured from the output of inverter and decoupled using the abc-dq transformation. The decoupled voltage and currents \((V_d, V_q, I_d, I_q)\) are used to calculate the \(I_{dref}\) and \(I_{qref}\) through Equation (1)\(^8\)-\(^10\).

\[
I_{dref} = \frac{2}{3} \frac{P_{ref}}{V_d}
\]

\[
I_{qref} = \frac{-2}{3} \frac{Q_{ref}}{V_d}
\]  

(1)

The Maximum solar power is taken from the MPPT as the power reference. However, when the battery is fully charged, the curtailment power control is initiated and no dump load is required. In the inner loop current control, the decoupled currents and the references value are then compared and passed through a PI controller to eliminate the error\(^11\). The resulting voltage references will be converted back to three phase to generate the PWM for the inverter.

### 3.2 VF Control with Droop Concept

The proposed VF control with droop concept shown in Figure 3 is implemented for the battery bi-directional inverter to regulate the AC bus voltage and frequency within the standard limits. The inner loop is similar to PQ control, while the outer loop is different. The outer control loop utilizes a droop concept whereby the frequency and voltage are governed by the active and reactive power respectively based on equation (2)\(^12\)-\(^13\). VF control with droop concept ensures that the voltage and frequency of AC bus are within the standard range.

\[
f_{ref} = f_o + M (P_o - P)
\]

\[
V_{ref} = V_o + N (Q_o - Q)
\]  

(2)

In order to verify the implemented control strategies, the modes of operation in Table 2 was adopted.

### Table 2: Modes of Operation

<table>
<thead>
<tr>
<th>Modes of Operation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 0 (Initialization)</td>
<td>Power produced by PV and wind turbine is more than the load demand. Excess power is used to charge the battery.</td>
</tr>
<tr>
<td>Mode 1 (PV, Wind &amp; Battery)</td>
<td>Power generated by PV and wind turbine is insufficient to supply the load demand. Battery discharges power to meet the load demand.</td>
</tr>
<tr>
<td>Mode 2 (PV, Wind &amp; Battery)</td>
<td>The battery is fully charged. The power produced by PV and wind turbine will exactly match the load. (Curtailment of real power initiated)</td>
</tr>
<tr>
<td>Mode 3 (Wind &amp; Battery)</td>
<td>When PV is unable to generate any power, the load demand is supplied by wind and battery.</td>
</tr>
</tbody>
</table>

### 4. Simulation and Analysis

The hybrid system is simulated in PSCAD/EMTDC for 48 hours to test and analyze the performance and response of the hybrid power system. The weather data is provided by the Meteorological Department as shown in Figure 4. The weather data is used as the input for simulation of the photovoltaic and wind. The battery was assumed to be at 90% SOC at the beginning of the simulation. The
temperature of Sandakan is assumed to have an average of 25°C and the simulation was carried out from 7.00 am. The simulation is assumed to start from 7am and ran for 2days in this case study. The analysis of power output is separated into 3 regions for better analysis as shown in Figure 5. The daytime of first day is defined as region 1 which is from 10am to 7pm. At region 1, the solar power is abundant and the wind is considered stable. This shows that the power generated from solar and wind are able to supply the load and the excess power charges the battery. At 1pm, the battery is fully charged. The battery received 27.9 kW from the solar PV to be fully charged. The solar inverter will switch to curtailment power control to match the power with the load demand. This was done without using a dump load to absorb the excessive power. At about 6pm, the sun sets and the generated solar power reduces. At this moment the output of the solar PV is lower than the load, the battery starts to supply power to the load to balance the load demand.

Region 2 is classified from 7pm to 7am. During the night time, the battery acts as the main power to supply the load. From 7pm to 12 am, the wind power is weak and the battery have to discharge more power to match the load demand. At 1am, the wind speed starts to become stronger and more wind power is generated. So, the battery power is reduced as the wind power is able to partially supply the load.

Region 3 is classified in day 2 from 7am to 4pm. The solar radiation of day 2 is low and the wind speed is weak. During 12pm to 1pm which is the lunch peak hour, the wind is unable to supply any power. Without the wind power, the solar power alone cannot meet the load demand. During this period, the battery switch from charge to discharge mode to balance out the load. After 1pm, the load demand decreases, and the renewable sources are able to meet the load demand. The excess power will be used to charge the battery. A total of 19.53kW was stored in the battery during this period.

Figure 4. Solar Radiation and Wind Speed for 2 days in Sandakan.

Figure 5. The output power of the hybrid system.

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Figure 6. The voltage of AC Bus Figure 7. The frequency of AC Bus.

The hybrid system proposed in this paper works as designed for all weather conditions based on the simu-
lation results. The voltage of AC bus fluctuates between 380V and 420V as shown in Figure 6. The frequency of the system shown in Figure 7 remains within 49.5 Hz and 50.5 Hz throughout the simulation. This does not violate the voltage and frequency limit stipulated in the distribution code.

5. Conclusion

This paper proposed a solar wind hybrid system for rural electrification in Sandakan. The simulation results shows that the hybrid system designed is able to support the load demand for two days and worked well for different weather conditions. The V/F control with voltage outer loop and inner current loop was able to maintain the frequency and voltage within the limits stipulated in the distribution code. The PQ control with real power curtailment features is able to regulate the excess power generated without using dump load. Hence, the proposed control strategy can be implemented for rural electrification using solar wind hybrid system in Malaysia.

6. Reference