Simulation and Control of a Hybrid PV-Wind System

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Abstract

Hybrid PV-wind generation shows higher availability as compared to the PV or wind alone. Simulation and control of a hybrid PV-wind generator system connected to the grid are presented in this paper, where every major component of the system is modelled, and then different control strategies are applied to the system. Design and sizing of the power electronic converter components which may be shared by both, and development of the control strategy, are the main aim of the simulation exercise. The system is connected to the grid so that the overall design objective is to maximize the power exported to the grid within the device ratings and the constraint of the grid capability.

I. Introduction

Solar and wind energies, among other renewable energy sources, are the most available and distributed in all over the world. Applications with photovoltaic (PV) and wind have been increasing significantly due to the rapid growth of power electronic techniques. Generally, PV power and wind power are complementary since sunny days are usually calm and strong winds often occur on cloudy days or in nighttime. The hybrid PV-wind power system therefore has higher availability to deliver continuous power and results in a better utilization of power conversion and control equipment than either of the individual sources. A simulation and control study of a hybrid PV-wind generator system connected to the grid is proposed in this paper. Every major component of the system is modelled, and then the control strategies are applied to the system. Fig. 1 shows a simple diagram of the different components of the hybrid system connected to the grid. The PV generator is controlled by a DC/DC boost converter, where the duty ratio (Dpv) is used as the control means to track the maximum power point. The power generated from the PV generator is supplied to the DC busbar, where a grid connected inverter is used to supply the total generated power to the grid. The wind generator consists of a wind turbine directly driving a permanent magnet generator (PMG) with a power electronic system that connects the wind turbine generator to the grid. The power electronic interface consists of; an uncontrolled rectifier, a boost DC/DC converter and the grid inverter that is shared with the PV generator.

The DC busbar voltage (Vbus) is adjusted as constant by means of the power angle (\(\delta\)), which is the phase angle between the grid voltage and the voltage on the inverter output. The volt-ampere reactive (VAR) is controlled by a control loop using the amplitude modulation index (Md) in the PWM process of the inverter. A statistic model of the wind speed [1] and a statistic model of the solar radiation are used as the inputs for the wind generator and the PV generator respectively. The single-phase grid inverter, boost converters on both generator sides are modelled by their local average behaviour ignoring the switching transient. In the following sections, the different components of the system will be modelled, and the control strategies will be designed for the different parts of the system. Then simulation results using SIMULINK are presented for the whole system.

II. PV Generator Model

The PV generator is an array of PV modules connected in series and parallel. A simplified equivalent circuit of a solar cell consists of a diode and a current source which are connected in parallel. The photocurrent generated when the sunlight hits the solar cell can be represented with a current source and the P-N transition area of the solar cell can be represented with a diode. The shunt and series resistances represent the losses due to the body of the semiconductor and the contacts respectively. Such an equivalent circuit of the solar cell is shown in Fig. 2 [2-3].

The voltage and current relationship in the simplified solar cell model can be derived from Kirchhoff's current law. According to Kirchhoff's current law, all currents entering and leaving a node add up to zero.

\[
I = I_{\text{light}} - I_{\text{diode}} - I_{\text{sh}} \quad (1)
\]

Then the output current can be calculated as in Eq. 2. In this equation, the last term can be neglected by assuming that the shunt resistance (Rsh) is very large. Eq. 2 is the solar cell model which can be used as one aggregated module model by considering the whole module working as a large area solar cell.

\[
I = I_{\text{light}} - I_o(e^{\frac{V+IR}{A}} - 1) - \frac{V + IR}{R_{\text{sh}}} \quad (2)
\]

where

\[
A = \frac{mKT}{q} \quad (3)
\]

In order to predict the performance of the photovoltaic module it is necessary to determine the operating cell temperature. For simplicity, the temperature of the solar cell is assumed homogeneous on the plane of the module. The cell temperature can be calculated from the equation of
energy balance around the PV cell. By a conventional analysis for the energy out and into the solar cell, the following equation for cell temperature can be derived.

\[ T_c = T_a + \frac{S}{S_{ref}}(T_{c,ref} - T_{a,ref})(1 - \frac{\eta_{PV}}{0.9}) \] (4)

The last equations were implemented in SIMULINK to simulate a PV generator on a Durham University building roof and the data sheet characteristics of one solar module, which is from the type Astropower PV-AP-95. This PV generator is an array of (12) modules connected in series, and every module consists of (36) monocrystalline solar cells. The simulated voltage against power characteristics for different sun radiation and cell temperature conditions are shown in Fig. 3.

\[ T_m = 0.5 \rho ARv^2 C_p(\lambda)/\lambda \] (5)

where \( \lambda \) is the tip speed ratio that can be calculated from the following Eq. 6.

\[ \lambda = \frac{R \omega}{v_s} \] (6)

The motion equation of a wind turbine is expressed by Eq. 7 by neglecting the mechanical losses.

\[ T_m - T_e = J \frac{d\omega}{dt} \] (7)

If a lossless and unloaded PMSG is considered, then the generator line voltage can be described by Eq. 14.

\[ v_{L-L-W} = K_i \omega_s \sin \omega_s t \] (8)

**III. Wind Generator Model**

The wind generator subsystem consists of a wind turbine connected to a Permanent Magnet Synchronous Generator (PMSG) as shown in Fig. 1. We have considered that the blades are rigidly attached to the wind turbine; consequently the pitch angle of the blades is fixed, then the wind turbine mechanical torque produced by the wind energy, which drives the PMSG, can be modelled by Eq. 5 [4-5].
By looking from the DC side of the rectifier, the PMSG can be modelled as a DC voltage source \((V_w)\) and a series potential drop to represent the commutation overlap of the rectifier and the winding series resistance of the PMSG, as shown in Fig. 4. The series potential drop is the summation of the drop in the DC voltage due to the generator coil inductance and resistance Eq. 9, which can be modelled as an equivalent series resistance \((R_w)\). From the equivalent circuit of the system shown in Fig. 2, the DC rectifier voltage can be calculated from Eq. 10.

\[
R_w = 2R_s + \frac{3\omega L_s}{\pi} \quad (9)
\]

\[
V_w = \frac{3\sqrt{2}}{\pi} V_{L-W} - R_w V_{bb} \quad (10)
\]

**Fig. 4 Circuit diagram for the wind generator connected to the grid**

A 2.5 kW 250 rpm wind generator voltage (viewed from the DC side of the rectifier) against power characteristics with different wind speeds is shown in Fig. 5. A dump resistance is used to brake the generator when it runs above the rated speed.

**Fig. 5 Wind turbine generator characteristics in output**

**IV. System Control**

Maximum power point tracking (MPPT) controllers are proposed to make the wind and the PV generators work in the maximum power mode that increases the energy captured from the wind speed and the solar radiation. Another controller is proposed to adjust the DC busbar voltage at the input of the inverter supplying the utility grid and the VAR supplied to the grid.

**IV.1. MPPT controller for PV generator**

The PV generator is a DC source, with its output characteristics depending on the solar radiation, temperature and the load condition (Fig.3). To maximize the output power of the PV generator, a maximum power point tracking controller is implemented in the system. The controller proposed by measuring only the current in the output of the DC/DC converter. Due to the constant DC busbar voltage in the output of the boost converter, the power can be maximized by maximizing the boost converter output current. This method is simple and suitable for this application.

**IV.2. MPPT for wind generator**

The wind generator is an AC source of power, with its characteristics nonlinearly changing with wind speed and load condition (Fig.5). An MPPT controller is also implemented to maximize the output power of the wind generator. The DC/DC boost converter is used to maximize the power by measuring the DC output voltage of the rectifier \((V_{boost,w})\) at the input of the boost converter and according to the curve fitting of the power against voltage \((P_{mpp}, V_{mpp})\) characteristics; the maximum power is obtained. A block diagram showing the maximum power point tracking control loop is shown in Fig. 6 [7].

**Fig. 6 MPPT control loop**

**IV.3. The inverter side control**

A voltage control loop is proposed to adjust the DC busbar voltage \((V_{bb})\) to a constant value of 600 V for this single phase inverter. The control loop is shown in Fig. 7 where the angle \((\delta)\) between the AC output voltage of the inverter \((V_a)\) and the grid AC voltage \((V_g)\) is controlled to regulate the DC busbar voltage at the required value. The output voltage amplitude is controlled to regulate the VAR supplied to the grid. From the simple circuit shown in Fig. 7, the reference grid side voltage can be determined in the controller to adjust the required output VAR.
V. Simulation Results
Simulation results of the hybrid PV-wind generator are proposed in this section. The section is divided into three parts: the PV generator side, the wind generator side, and the grid side simulation results. The results show that the control strategies applied successfully achieved the desired system performance. The results from simulation are used to design the power electronic components in the system.

V.1. PV generator side output characteristics
The inputs of the PV generator are the solar radiation and ambient temperature (Fig 1) where both of them are changing at random values. The solar radiation is changing between 0-1000 W/m² and the temperature is changing around 20 °C. Figure 8 shows the input solar radiation, the PV generator output power, the PV generator output current, and the PV generator output voltage. The figure shows that as the output PV current changes to maximize the power output to the load the output voltage is almost constant and that due to the small range of change in the DC voltage. The target maximum power for the controller compared to the output power is shown in Fig. 9 where the MPPT tracks the power accurately.

V.2. Wind generator side output characteristics
The simulation output for the wind generator side is shown in Fig. 10. The figure shows the wind speed in m/s as the input, the DC output current from the bridge rectifier, the DC output voltage, the generator output power. The DC voltage at high wind speed is almost constant and that due to the constant rotational speed. The rotational speed kept constant with the dumping resistance switched in at high wind speed for generator protection. The MPPT validity of the controller is shown in Fig. 11 where the target maximum power is shown against the output power from the wind generator. This tracker has an advantage with other trackers as we do not need to measure the shaft speed of the generator, and that make the tracker practically more reliable due to the difficulties of measuring the shaft speed.

Fig. 8 Simulation output in the PV generator side

Fig. 9 Output power against target MP for PV generator

Fig. 10 Simulation output in the wind generator

Fig. 11 Reference MP and actual output power in wind generator-converter side

V.3. The grid connected side
The simulation output of the hybrid PV-wind generator system on the grid connection side is shown in Fig. 12. The figure shows the VAR and the DC busbar voltage. There are two control actions on this side, the first one adjusting the DC busbar voltage and the other supplying the required VAR to the grid as mentioned in section (VI.3). The DC busbar voltage controller adjusts the voltage a constant value of 600 V, and Fig. 12 shows that the controller achieves the target with high stability even with continuous change in the power generated from the PV and wind generators.

Fig. 12 shows the VAR controller where the VAR is adjusted to be 0 VAR. As shown from the Figure, there are only small variations corresponding to the change of real power.

**VI. Conclusion**

This paper presents a simulation and control study for a hybrid PV-wind generator system connected to the grid. The different components of the system were modelled and the control strategies for the different parts of the system were proposed. The simulation process illustrated the currents and voltages in the different components of the system with different input conditions of solar radiation, wind speed and temperature. The control objective of the system is achieved and the controllers are designed.

**References**