Study of a standalone microgrid with multiple distributed energy resources

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Abstract

A standalone hybrid microgrid with Photovoltaic(PV), Wind energy conversion system(WECS), Diesel generator and a battery backup unit is investigated in this paper. A simple Power Management Strategy(PMS) is implemented and the performance of the microgrid is studied under different climatic and load conditions. A control strategy is implemented to control active(P) and reactive power(Q) of the microgrid. The quality of power is studied for different types of load. The results show that the proposed strategy can maintain the power quality in the hybrid microgrid without the support of the utility grid and is capable of supplying uninterrupted power to the load even under changing conditions of load. The results also demonstrate coordination between the PV MPPT and power control loop. MATLAB/SIMULINK is used for simulation.

Keywords: Active power and reactive power control, Boost converter, Distributed energy resources(DERs), Energy Storage System(ESS), Fuzzy Logic Controller, Inverter, Maximum power point tracking(MPPT), Power management strategy(PMS), State of charge(SoC)

1. Introduction

A standalone microgrid is an independent electric supply system powered exclusively by Distributed Energy Resources(DERs) with a Energy Storage System(ESS) for backup. Unlike conventional microgrids which are connected to the utility, these standalone microgrids are capable of supplying the load demand without the support of the utility grid and are therefore not connected to them. A major issue pertaining synchronization and control arises when DERs are integrated with the grid[1][2][3]. This issue is eliminated when DERs function independent of the grid. However, such a system faces its own difficulties with respect to control and power quality. This paper shows strategies that can solve these issues and provide uninterrupted, quality power to the load.

The system under consideration consists of the following sources: PV panel, WECS, diesel generator and a lead-acid battery as back up for PV. This paper is split into two parts. The first part demonstrates the PMS and the second part deals with active and reactive power control.
So far the work done by various scholars in this direction incorporates either of the two parts of research[4][5][6][7][8][9][10]. This paper brings together two of the most important concerns related with standalone microgrids and suggests solutions for the two. Most three phase supplies are used to power static as well as dynamic loads in an industrial or domestic environment. The behavior of the system is investigated for static load(RL load) and dynamic load(Induction motor) load.

The structure and focus of this paper is on the MPPT for the PV using a fuzzy logic controller, PQ control for the PV, strategy to control SoC of the battery, pitch angle control of the WECS and overall PMS

1.1 PV Panel

The Photovoltaic panel consists of several PV cells arranged in series and parallel to meet the requirements of output voltage, current and ultimately power[22][23][24][25]. The PV cell can be represented mathematically using the one diode equivalent model as shown in Fig. 1.

The relationship between current and voltage in the single-diode equivalent circuit is:

\[ I = I_{ph} - I_s(e^\frac{(qV+IR_s)}{\Delta kT}-1) - \frac{(V+IR_s)}{R_{sh}} \]  

(1)

where, \( I_{ph} \) is photocurrent; \( I_s \) is diode saturation current; \( q \) is coulomb constant (1.602e-19C); \( k \) is Boltzman’s constant (1.381e-23 J/K); \( T \) is cell temperature (K); \( A \) is P-N junction ideality factor; \( R_s \) and \( R_{sh} \) are intrinsic series resistances. The PV panel considered in this system is the Kyocera GT200 panel with 125 strings in parallel and 4 cells in series per string. The total output power capacity of the panel is 100kW[2]. The characteristics of current and power are nonlinear with varying irradiance and temperature. Fig.2. shows the nature of current and power with change in irradiance at 25 deg centigrade temperature. The nature of current and power with change in temperature at 1000W/m² irradiance is shown in Fig.3.
The parameters of a single PV cell of Kyocera GT200 are shown in Table 1.

Table 1. Kyocera GT200 parameters at 1000Ω/μ2 irradiance and 25°C

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_MPP</td>
<td>200.143W</td>
</tr>
<tr>
<td>V_MPP</td>
<td>26.3V</td>
</tr>
<tr>
<td>I_MPP</td>
<td>7.61A</td>
</tr>
<tr>
<td>V_OC</td>
<td>32.9V</td>
</tr>
</tbody>
</table>
1.2 DC-DC Boost converter

Fig.3 shows the circuit diagram of a dc-dc boost converter. The relationship between output voltage $V_o$ and input voltage $V_i$ is given by equation (2)

$$\frac{V_o}{V_i} = \frac{1}{1-D}$$

(2)

The output voltage can be controlled by varying the duty cycle $D$ as observed from equation (2). The converter operates in two modes. First when switch is closed, the inductor gets charged by the source. The current through inductor is assumed to be linearly varying for simplicity. The capacitor on load side discharges and supplies power to the load. The diode restricts back flow of current. The second mode is when switch is open. The diode is forward biased. The inductor discharges and charges the capacitor along with the source and meets the load demands. The load current variation is very small and is considered in designing. For designing the inductor and capacitor the following equations are used:

For inductor

$$L = \frac{V_o \times D}{(\Delta I \times f)}$$

(3)

For capacitor

$$C_2 = \frac{D}{(R \times \Delta V_o/V_o \times f)}$$

(4)

Where $R$ is load resistance, $f$ is the switching frequency, $\Delta V_o/V_o$ is the output ripple voltage and $\Delta I$ is variation in load current. $C_1$ is chosen to achieve smooth DC at input of converter. The design parameters of the boost converter are as shown in Table.2.

<table>
<thead>
<tr>
<th>L</th>
<th>2.323mH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_2$</td>
<td>1mF</td>
</tr>
<tr>
<td>$F$</td>
<td>20kHz</td>
</tr>
</tbody>
</table>

The switch is controlled by providing PWM pulses with the help of a FLC based MPPT controller for the PV panel. Input membership functions are change in current and change in power whereas change in duty cycle is the output membership function. The rule base
applied to the FLC are as shown in the Table.3.

<table>
<thead>
<tr>
<th>Δd</th>
<th>ΔP</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔI</td>
<td>NH</td>
</tr>
<tr>
<td>NH</td>
<td>NH</td>
</tr>
<tr>
<td>NL</td>
<td>NL</td>
</tr>
<tr>
<td>ZZ</td>
<td>ZZ</td>
</tr>
<tr>
<td>PL</td>
<td>PL</td>
</tr>
</tbody>
</table>

1.3 Battery

A Lead-acid battery of 100kW capacity is chosen to provide backup to the PV panel for up to 1 hour at full load[20][21][22][23][24]. The battery is charged with the PV panel when load demand is low. SOC of 20% to 80% is maintained. If the Ppv is greater than Pbat, Ppv supplies to the load and vice versa. Fig. 5. Shows the selection criteria between PV and battery. The bidirectional converter used for battery is shown in Fig. 6.

![Figure 5](image)

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Switch 1 is ON in buck mode when the battery is charging while Switch 2 is OFF. Switch 2 is ON during boost mode when battery is discharging and Switch 1 is OFF.

1.4 WECS

A variable speed wind turbine with Permanent Magnet Synchronous Generator(PMSG) is used. The capacity of the WECS at wind speed of 12m/s is 100kW[26]. Fig. 7 shows the MATLAB model based design of the wind turbine. This model is used to generate the torque required for the PMSG. The readily available PMSG model in MATLAB is used. The output of the WECS is rectified and connected to the common inverter used to supply three phase AC to the load.
1.5 Diesel generator

To facilitate full back up, a 100kW diesel generator set is provided to ensure uninterrupted power supply is a scenario when both PV and WECS are incapable to supply enough load and battery is completely discharged.

2. PROPOSED MODEL

The model under study is as shown in Fig. 8.
The output of the DERs are all in DC and are connected to the input of a common three phase inverter. The load is connected to output of inverter. The instantaneous active and reactive power at the output of the inverter is given by equations (5)-(9).[2]

\[ P(t) = \frac{1}{T} \int_{t-T/2}^{t+T/2} v_t(\tau) i_c(\tau) \, d\tau = \frac{V_v(t) V_c(t)}{oL_C} \sin \alpha \quad (5) \]

\[ S(t) = V_t(t) i_c(t) = \frac{V_v(t)}{oL_C} \sqrt{V_v(t)^2 + V_c(t)^2 - 2V_v(t) V_c(t) \cos \alpha} \quad (6) \]

\[ Q(t) = \sqrt{S^2(t) - P^2(t)} = \frac{V_v(t)}{oL_C} \left( V_c(t) \cos \alpha - V_v(t) \right) \quad (7) \]

\[ P(t) \approx \frac{V_v(t) V_c(t)}{oL_C} \alpha \quad (8) \]

\[ Q(t) \approx \frac{V_v(t)}{oL_C} \left( V_v(t) - V_c(t) \right) \quad (9) \]

Where \( T \) is time period, \( v_t(\tau) \) and \( i_c(\tau) \) are instantaneous voltage and current, \( V_c(t) \) is the voltage at the DC link, \( \alpha \) is the triggering angle.

### 2.1 Power management strategy

When multiple resources are connected to a single point of common coupling, it is important to manage them in a way that the load demand is met. Block diagram of the model under study is as shown in Fig. 9.
A priority is assigned to each of the resources to meet the load demand. The priority is as explained in the following algorithm:

- Measure the power generated by Solar, WECS, Battery, Diesel and the power demand of the load
- If power generated by PV panel is equal to load demand, PV alone supplies to the load
- If PV power is greater than the load, PV alone supplies to load and also charges the battery if Battery SOC is less than 80%
- If PV power is less than demand, battery discharges and supplies to load until Battery SOC reaches 20%
- If power of PV is less than load demand, battery SOC is 20% or less and WECS power is greater or equal to load demand, WECS alone supplies to the load
- If power PV, battery and WECS is less than load demand, Diesel generator alone supplies to the load.

2.2 Active and reactive power control

Particularly when the PV panel is supplying to the load which has the highest priority as a source in this model, the control of active and reactive power is necessary. Three PI controllers are used for this. It is carried out as shown in Fig. 10. The equations governing the control loop are as shown in equation (10)- (13). [2]

\[ v_{c1} = (K_{P2} (Q_{ref} - Q_{actual}) + K_{I2} \int_{0}^{t} (Q_{ref} - Q_{actual}) dt + 1) v_t \] (10)

\[ a_1 = K_{P3} (P_{ref} - P_{actual}) + K_{I3} \int_{0}^{t} (P_{ref} - P_{actual}) dt \] (11)

\[ a_2 = K_{P4} (1.02 \times P_{ACmeasured} - P_{DC}) + K_{I4} \int_{0}^{t} (1.02 \times P_{ACmeasured} - P_{DC}) dt \] (12)

\[ a^* = (a_1^* + a_2^*) / 2 \] (13)
3. RESULTS

To verify the performance of the standalone microgrid, the following cases are considered.

Case 1:

When the irradiance is 1000W/m² and temperature is 25°C. In this case power generated by the PV panel is sufficient to supply the load demand. The load is of RL type with active power consumption of 1.65kW. The PV panel voltage, current, current through equivalent diode, irradiance and temperature are as shown in Fig. 11.
The active power supplied to load is shown in Fig. 12.

The simulation is carried out for 5 seconds which is sufficient for the settling of the output from the PV panel. The load active power consumption is 1.65kW as observed in Fig. 12. The reactive power consumption is shown in Fig. 13.

In this scenario, the battery is not being discharged and the initial state of charge is maintained at 49.9%. This is shown in Fig. 14.
The current from battery during this case is zero as seen in Fig.14. Also the voltage is maintained at the open circuit value of the battery. The battery does not discharge in this case. Initial state of charge is 50% and the small loss in charge is due to leakage.

**Case 2:**

In this case the PV panel output is not available. In this scenario, the battery supplies to the load. The load Active and Reactive powers are shown in Fig.15 and Fig.16. The battery Voltage and current and SoC are shown in Fig. 17.

Since the battery alone is supplying to the load in this case, the reaction time is close to 2 seconds as observed in Fig.15. This time is due to the decisions to be taken by the PMS and the PQ control loop.
The reactive power consumption in this case is considerably low due to the change in load.

From Fig. 17 we observe that the battery rapidly discharges from the initial 80% SoC indicating that it is in boost mode and supplying to the load. In this case the irradiance of the PV panel is considered to be zero, indicating the night hours. However the results were also true for values of low irradiance as well.

**Case 3:**

In this case both PV and battery are incapable of meeting load demand. The WECS alone supplies to the load. Since PMSG is used, both P and Q demands are met. Fig. 18 shows output of the WECS. Fig. 19 shows the Active power delivered to load and Fig. 20 shows reactive power.
Since the output of the WECS-PMSG is a 3-ph AC, a rectifier circuit is used to convert it into DC before supplying to the input of common inverter, Fig. 18 shows the DC output voltage and current of the WECS.

The settling time is observed to be 0.6 seconds. The load demand is met by WECS alone in this case.
Since the PMSG is used, the reactive power need not be supplied externally and the WECS itself is capable of supplying it. This can be observed in Fig. 20

Case 4:
In this case, diesel generator alone is supplying power to the load. Fig. 21 shows the output of diesel generator. Fig. 22 and Fig. 23 respectively show the active and reactive power of the load.

From Fig. 21 it can be observed that the diesel generator is capable of supplying to the load to provide full backup in case of unavailability of all other DERs.
At same load demand when wind speed is less than 12m/s and the PV panel is not generating any power and battery SoC is less than 20%, the diesel generator supplies the power to the load.

This case can be considered as worst-case scenario with respect to the DERs. The Fig.22 and Fig.23 show the active and reactive power to the load and confirm that the uninterrupted supply of power is maintained even when only diesel is supplying.
4. CONCLUSION

A solar with battery backup, WECS and diesel generator powered standalone microgrid which makes use of a Kyocera GT 200 solar panel and a WECS with PMSG was implemented. The system has reliable uninterrupted power supply. The performance of the microgrid was studied under different conditions of weather and load. However the supply voltage to the load is chosen to be 100V which is exclusively to demonstrate the working of this system. With future work, the standard voltage of 480V can be achieved with minor design changes.
5. References


