PV Output Power Fluctuations Smoothing and Optimum Capacity of Energy Storage System for PV Power Generator

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Abstract. In this paper, an Energy Storage System (ESS) based control method is proposed to reduce the PV output power fluctuations, which in turn will reduce the frequency deviations of the power system introduced by large penetration of PV power. The ESS control model introduced here will maintain the energy storage ratio of the ESS near 50%. This will increase the life time of the ESS as well as will decrease the maintenance cost of the ESS. A local search algorithm is also provided with this ESS control model to search the optimal capacity of the ESS required for smoothing the PV output power fluctuations and to find the minimum capital cost. A cost comparison is shown to realize the performance of the search algorithm.

Key words
Capital cost, Energy Storage System, Optimal capacity, PV output power smoothing.

1. Introduction

In recent times, Global warming is a burning issue as the CO₂ density increased highly in the atmosphere. Therefore, clean and renewable energy sources must be introduced to reduce the CO₂ density. Among various renewable energy systems, PV systems are expected to play a promising role as a clean power electric source in meeting future electricity demands. However, the power output of PV systems fluctuates depending on weather conditions, season, and geographic location. In the future, when a significant number of PV systems will be connected to the grids of power utilities, power output fluctuation may cause problems like voltage fluctuation and large frequency deviation in electric power system operation [1]-[3]. Therefore, for the penetration of large PV system’s output power in the utility without reduction of the reliability of utility power systems, suitable measures must be applied to the PV systems side.

On the PV system side, energy storage devices like batteries can be used as smoothing devices for a PV system’s output. There have been investigations aimed at improving the performance of PV systems equipped with batteries [4]-[9]. However, energy storage device increases capital cost, as it needs maintenance. The maintenance cost mainly depends on charge/discharge action of battery. Therefore, controlling the charge/discharge action along with maintaining the energy storage ratio near 50% is a issue need to be addressed. Besides, optimal capacity and minimum capital cost of the ESS needed to reduce the PV output power fluctuations should also be investigated. However, in previous investigations, the optimal size of battery and battery parameters for charge/discharge action are not considered.

In this paper, to address the above given issue, a control methodology for ESS along with PV generator is presented, which will maintain storage energy ratio of the battery up to 50% and will select optimal size of the battery needed for smoothing PV output power fluctuations. From the simulation results, it has been found that the proposed method works well to reduce the PV output power fluctuations and also selects the optimal ESS capacity needed for it maintaining the energy storage ratio near 50%.

2. Small Power System

The concept of small power utility in this paper is shown in Fig. 1. The small power utility consists of the diesel generators and PV systems equipped with ESS that generate power to supply the demand. In addition, it is assumed that the small power utility is not connected to large power utility and it is always operated independently like the power system in an isolated island. The small power system model which consists of diesel generator in detail, PV power generation system, load and Energy Storage system, and load is shown in Fig. 2 where $S_i$ is the insolation, $P_{\text{max}}^*$ is the maximum power

![Fig. 1. Small power utility.](https://doi.org/10.24084/repqj06.213)
point tracking (MPPT) command power, $P_{bat}$ is the battery power, $P_{pvsys}$ is the PV power by PV supplied to the power system, $P_d$ is generated power by diesel generators, $R$ is the speed regulation, $T_g$ is the governor time constant, $T_d$ is the diesel generator time constant, $P_L$ is the load, $M$ is the inertia constant, $D$ is the damping constant, $u$ is the input to the governor, $\Delta f$ is the frequency deviation of small power utility.

The control algorithm [10] for the inverter shown in Fig. 1 adopted here is very simple. The inverter output voltages and currents are sensed and transformed from 3-phase to synchronously rotating 2-phase. The command currents are generated dividing the output power command by sensed inverter voltage. Then the error between command inverter current and actual inverter current is processed through a PI controller to generate the PWM pulses. For maximum power extraction, the output power command is generated by maximum power point tracking algorithm. For simple structure and less costly implementation, a Perturbed and Observed (P&O) [11] algorithm was chosen in the present structure.

As the design of power converter and the control system is significantly influenced by the solar module characteristics, these will briefly reviewed here. The solar module is a nonlinear device and can be represented as a current source model, as shown in Fig. 3. The traditional $I-V$ characteristics of a solar module are given by the following equation [12]:

$$I_0 = N_p N_s I_{sat} \left\{ \exp \left( \frac{q(V_0 + N_s R_s I_0)}{AKT_a} \right) - 1 \right\} - I_{rsh}$$

where $I_0$ and $V_0$ are the output current and output voltage of the solar module, respectively, $I_{sat}$ is the generated current under a given insolation, $I_{sat}$ is the reverse saturation current, $q$ is the charge of an electron, $K$ is the Boltzmann’s constant, $A$ is the ideality factor, $T_a$ is the temperature (K), $N_p$ is the number of cells in parallel, $N_s$ is the number of cells in series, $R_s$ is the internal series resistance, and $I_{rsh}$ is the current due to intrinsic shunt resistance of the solar module.

The solar module output power is given by the following equation:

$$P_0 = V_0 I_0$$

Equations given in (1) and (2) are used in the development of computer simulations for the solar module. The MATLAB/SIMULINK is used. Fig. 4(a) and (b) shows the simulated ampere-volt and power-volt curves of the solar module for different insolation at constant temperature. Figs. 4(c) and (d) show the simulated ampere-volt and power-volt curves of the solar module for different temperature at constant insolation. From these curves, it is observed that the output characteristics of the solar module are nonlinear and vitally affected by the variation of insolation. However, variation of temperature slightly affects the output characteristics of solar module. Therefore, for the present case study, insolation and temperature variation effects both are taken in to account to model the solar array.

### 3. Battery Control Method

In order to smooth PV output power fluctuations, average PV power is generated from MPPT generated PV power through a low pass filter. The average PV power is given by the following equation

$$P_{avg} = P_{max} f(s)$$

where $f(s) = \frac{0.9}{20s + 1}$

This average power is used as command power for the battery control system. Therefore, this command power
will be achieved from the PV system by charging/discharging action of the Battery. The proposed battery control model is shown in Fig. 5.

At first the proposed model calculates PV output power fluctuations by the given below equation.

\[ \Delta P_{\text{pvsys}} = P_{\text{avg}} - P_{\text{max}} \]  

(4)

where \( \Delta P_{\text{pvsys}} \) is PV output power fluctuations. To reduce the charge/discharge action of the battery, a definite value for the dead zone \( \text{Dzone} \) is set. Dead zone will activate when \( \Delta P_{\text{pvsys}} \) is greater than the dead zone value. Therefore, if the dead value is set big, small PV power fluctuations will remain in the system. On the other hand, if the dead zone value is set small, PV output power fluctuations will be smoothed well, however, battery will experience rapid charge/discharge action. So, choosing the optimal parameter for battery control system is a vital issue. From Fig. 5, it can be seen that correction power \( cP \) is added with dead zone. Then, battery output \( P_{\text{bat}} \) is computed through the limiter whose maximum range is the converter capacity \( C_I \).

Battery experiences charge/discharge action when \( P_{\text{bat}} \) becomes positive/negative. The battery’s remaining capacity \( W_{\text{bat}} \) is calculated through integration. This integrator is also considered as a limiter whose maximum range is the battery capacity \( C_{\text{bat}} \). The remaining battery capacity \( W_{\text{bat}} \) is passed through a 2-D lookup table to maintain the storage ratio \( \xi (= W_{\text{bat}} / C_{\text{bat}} \times 100\%) \) to near 50%.

The lookup table is shown in Fig. 6. The lookup table produces a correction value \( M \). The product of correct value \( M \) and converter capacity \( C_I \) becomes the correct power \( P_c \).

4. Optimization of Battery Size and Cost

When searching the optimal size of the battery capacity and converter capacity, which will maintain minimum capital cost, optimal control parameters for battery control model should be searched. The searching algorithm is shown in Fig. 7.

Objective function and constraint condition are given in (5) and (6). Capital cost \( C_{\text{cap}} \) is calculated from (5). Here \( C_p \) is the per kWh capacity price of the battery and \( C_w \) is the per kW capacity of the converter [13].

\[ \min C_{\text{cap}} = C_B C_p + C_I C_w \]  

(5)

\[ \Delta P_{\text{pvsys max}} \geq \Delta P_{\text{pvsys}} \]  

(6)

The searching process for optimization is described as follows.

Step 1: Maximum output power fluctuation tolerance limit \( \Delta P_{\text{pvsys max}} \) is set.

Step 2: In this steps control parameters of ESS (\( M \), \( \text{Dzone} \)) are set.

Step 3: The charge/discharge action of battery is performed. \( \Delta P_{\text{pvsys}} \) is calculated. It searches \( C_B \) and \( C_I \) to minimize the capital cost using the local search which is shown in Fig. 8.

This step increases by a large width when it searches for optimal battery and converter capacities. Secondly, it searches by small width of increase. As shown in Fig. 8, this process iterated twice according to objective function. In order to prevent the convergence in local solution, it searches solution of three higher ranks to minimize the capital cost.
Step 4: The result of step 3 is evaluated. If it satisfies at end conditions, process terminated else it goes to step 2.

5. Simulation Results

In this paper, the effectiveness of output power leveling of PV array and frequency deviation reduction of power system using the proposed method is examined by simulation with system model and parameters as mentioned in [12]-[16]. In order to use parameters of real PV system given in [15], [16], the rated output power of the PV array is 241 kW. Simulation parameters of power system, PV array, power converter and PI controller are shown in TABLE III. Here, integral time $T_i$ to obtain discrete value of output power command is 10 s, and sampling time of PI controller is 1 ms. Simulation time is 30 minutes and the averaging sample time of insolation is 20 s.

TABLE II shows the simulation results for the optimization algorithm.

<table>
<thead>
<tr>
<th>Sl.</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
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<tr>
<td>$\Delta M$</td>
<td>0.002</td>
<td>0.001</td>
<td>0.002</td>
<td>0.007</td>
</tr>
<tr>
<td>$D_{pave}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\Delta P_{pvsys}$</td>
<td>±34 kW</td>
<td>±12 kW</td>
<td>±11 kW</td>
<td>±15 kW</td>
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<tr>
<td>$C_e$</td>
<td>60 kWh</td>
<td>160 kWh</td>
<td>180 kWh</td>
<td>200 kWh</td>
</tr>
<tr>
<td>$C_f$</td>
<td>130 kW</td>
<td>200 kW</td>
<td>170 kW</td>
<td>230 kW</td>
</tr>
<tr>
<td>Cost</td>
<td>237 k $</td>
<td>249 k $</td>
<td>381 k $</td>
<td>485 k $</td>
</tr>
</tbody>
</table>

The comparative simulation results of the proposed control and MPPT control [4] are shown in Fig. 9 by solid line and dotted line respectively. Insolation and load are shown in Figs. 9 (a) and (b) respectively. Fig 9 (c) shows the PV power produced by MPPT control and proposed control. From, Fig. 9 (c), it can be said that PV power produced by proposed method is levelled by battery charging/discharging action.
Fig. 9 (d) shows diesel power where diesel power produced by proposed method fluctuates less than the diesel power produced by MPPT control. Fig. 9 (e) shows the frequency deviations where frequency deviations produced by MPPT control are ± 1 Hz. On the other hand, frequency deviations produced by proposed method is almost near to zero. Therefore, it can be said that the proposed method is effective to reduce the frequency deviation of the utility. Fig. 9 (f) shows battery charging/discharging action. Fig. 9 (g) shows the storage energy ratio which is maintained below 50%, thus, it will reduce maintenance cost for the battery. So overall capital cost will be reduced as the optimum battery and converter capacity is used by the proposed method.

6. Conclusion

In this paper, PV output power fluctuations are levelled using the proposed methodology through battery charge/discharge action and the optimal size of the battery is calculated to minimize the capital cost. In the optimization problem of Energy Storage System (ESS), the control parameter for ESS is selected in all combinations and local search is performed to find the optimal size of the battery. The proposed method is compared with conventional MPPT. From the simulation results, it has been found that the proposed method is able to achieve the required control parameters for ESS and the optimal battery and converter capacities to minimize the total cost and to minimize the frequency deviations.

References