A novel two-mode MPPT control algorithm based on comparative study of existing algorithms

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Abstract

In this paper, the effectiveness of these three different control algorithms is thoroughly investigated via simulation and a proposed efficiency evaluation method of experimentation. Both the steady-state and transient characteristics of each control algorithms along with its measured efficiency are analyzed. Finally, a novel two-mode maximum power point tracking (MPPT) control algorithm combining the modified constant voltage control and IncCond method is proposed to improve the efficiency of the 3 kW PV power generation system at different insolation conditions. Experimental results show that the proposed two-mode MPPT control provides excellent performance at less than 30% insolation intensity, covering the whole insolation area without additional hardware circuitry.

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1. Introduction

As the conventional energy sources are rapidly depleting, the importance of solar photovoltaic (PV) energy has been emerging as replaceable energy resources to human being. Since it is clean, pollution-free, and inexhaustible, researches on the PV power generation system have received much attention, particularly, on many terrestrial applications. Furthermore, due to the continuing decrease in PV arrays cost and the increase in their efficiency, PV power generation system could be one of comparable candidates as energy sources for mankind in near future. As is well known, the maximum power point (MPP) of a PV power generation system depends on array temperature and solar insolation, so it is necessary to constantly track the MPP of the solar array. For years, research has focused on various MPP control algorithms to draw the maximum power of the solar array. Among them, the constant voltage control method, the perturbation and observation (P&O) method and the incremental conductance method (IncCond) have drawn attention due to the usefulness of each system. In this paper, the effectiveness of these three different control algorithms is thoroughly investigated via simulation and a proposed efficiency evaluation method of experimentation. Both the steady-state and transient characteristics of each control algorithms along with its measured efficiency are analyzed. Finally, a novel two-mode MPPT control algorithm combining the constant voltage control and IncCond method is proposed to improve efficiency of the 3 kW PV power generation system at different insolation conditions. Especially in cases in which solar insolation changes

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rapidly at lower insolation, the P&O and the IncCond MPPT control methods fail to track the MPP. The proposed two-mode MPPT control algorithm, however, works very well due to the adoption of the modified constant voltage control method.

2. Simulation model of the PV cell

Currently, various numerical models are in use by engineers investigating different aspects of photovoltaic technologies. The fundamental physics associated with solar cells are often studied using programs that model solar cell characteristics. Recent modeling of individual cells has used a highly distributed SPICE model. The proposed simulation program was designed to address the interactive behavior of modules in arrays by accurately simulating the electrical characteristics of individual cells in the modules.

The building block of the PV array is the solar cell, which is basically a p–n semiconductor junction that directly converts light energy into electricity: it has the equivalent circuit shown in Fig. 1 (Angrist, 1971). The current source \( I_{ph} \) represents the cell photo current; \( R_j \) is used represent the nonlinear impedance of the p–n junction; \( R_{sh} \) and \( R_s \) are intrinsic shunt and series resistance of the cell, respectively. Usually the value of \( R_{sh} \) is very large and that of \( R_s \) is very small, hence they may be neglected to simplify the analysis. A total of Samsung SM-60PV cells in Table 1 are grouped in larger units called PV modules, which are further interconnected in a parallel-series configuration to form 3 kW PV arrays.

Since solar cells are highly nonlinear, the characteristics of the PV array as shown in Fig. 3. The following set of equations are presented by a set of curves of a PV generator. \( I_{ph} \) is the cell photo current; \( R_j \) is the p–n junction ideality factor; \( T \) is the cell temperature (K); and \( I_{rs} \) is the cell reverse saturation current. The factor \( A \) in Eq. (1) determines the cell deviation from the ideal p–n junction characteristics. The ideal value ranges between 1 and 5, being the ideal value. In our case, \( A \) equals 2.15.

The cell reverse saturation current \( I_{rs} \) varies with temperature according to the following equation

\[
I_{rs} = I_{rs0} \left[ \frac{T}{T_r} \right]^3 \exp \left( \frac{qE_G}{kQA} \left[ \frac{1}{T_r} - \frac{1}{T} \right] \right)
\]  

where \( I_0 \) is the PV array output current (A); \( V_0 \) is the PV array output voltage (V); \( n_s \) is the number of cells connected in series; \( n_p \) is the number of strings connected in parallel; \( q \) is the charge of an electron; \( k \) is Bolzmann’s constant; \( A \) is the p–n junction ideality factor; \( T \) is the cell temperature (K); and \( E_G \) is the band-gap energy of the semiconductor used in the cell. The photocurrent \( I_{ph} \) depends on the solar radiation and the cell temperature as shown in the following equation

\[
I_{ph} = [I_{sc} + k(T - T_r)] \frac{S}{100}
\]

where \( Q \) is the electron charge, \( T_r \) is the cell reference temperature, \( I_{rs} \) is the reverse saturation current at \( T_r \), and \( E_G \) is the band-gap energy of the semiconductor used in the cell. The following parameters are used for modeling PV cells:

![Fig. 1. Equivalent circuit of a PV cell.](image)

### Table 1

<table>
<thead>
<tr>
<th>SM-60PV module</th>
<th>Catalogue data</th>
<th>Experimental results</th>
<th>Simulation results</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open-circuit voltage ( (V_{oc}) )</td>
<td>21.10</td>
<td>22.2</td>
<td>21.78</td>
<td>1.9</td>
</tr>
<tr>
<td>Short-circuit current ( (I_{sc}) )</td>
<td>3.80</td>
<td>3.92</td>
<td>3.77</td>
<td>3.83</td>
</tr>
<tr>
<td>Maximum power [W]</td>
<td>59.85</td>
<td>59.89</td>
<td>58.04</td>
<td>3.09</td>
</tr>
<tr>
<td>Voltage at load ( (V) )</td>
<td>17.10</td>
<td>16.66</td>
<td>17.03</td>
<td>2.17</td>
</tr>
<tr>
<td>Current at load ( (I) )</td>
<td>3.50</td>
<td>3.6</td>
<td>3.34</td>
<td>7.23</td>
</tr>
</tbody>
</table>

By making step variation in the solar radiation \( S \) and the cell temperature \( T \) in Eqs. (1)–(4), the proposed emulator of Fig. 2 provided the \( I-V \) and the \( P-V \) characteristics of the PV array as shown in Fig. 3.
intrinsic shunt resistance of the cell, $R_{sh}$: $5 \times 10^5 \, \Omega$;
intrinsic series resistance of the cell, $R_s$: 0.00005 A;
p–n junction manufacturing factor, $A$: 2.15;
number of strings in parallel, $N_p$: 4;
number of cells in series, $N_s$: 540;
cell short-circuit current at reference temperature, $I_{sc}$: 3.75 A;
cell temperature, $T$: 300 K;
cell reference temperature, $T_r$: 40 °F;
short-circuit current temperature coefficient, $k_i$: 0.00023 A/K;
reverse saturation current at $T_r$, $I_{rr}$: 0.000021 A;
electron charge, $Q$: 1.6022E-19.

From these curves, it is observed that the output characteristic of the solar array is nonlinear and severely affected by the solar insolation, temperature and load condition. Table 1 shows Samsung
SM-60PV module data given in catalogue, experimental data, simulation data and percentage error, respectively.

3. Proposed two-mode control algorithm for MPPT

As is well known, the MPP of PV power generation system depends on array temperature and solar insolation, so it is necessary to constantly track MPP of solar array. For years, research has focused on various MPP control algorithms to draw the maximum power of the solar array. Among them, the constant voltage control method, the perturbation and observation (P&O) method and the incremental conductance method (IncCond) have drawn many attention due to the usefulness of each system. In this section, the effectiveness of these three different control algorithms are thoroughly investigated via simulation and verified by proposed experimental efficiency evaluation setup.

The simulation circuit shown in Fig. 4, consists of the solar cell array (3.2 kW), capacitor bank, boost converter, and load. There are three dynamic link libraries (DLL) for the implementation of MPPT algorithm. Ms-user0 (DLL) is the simulator of the PV cell of Fig. 2 and ms_user4 (DLL) and ms_user9 (DLL) are used for the simulation of insolation variations and implementing the MPPT such as constant voltage control, P&O algorithm, IncCond algorithm and the proposed two-mode algorithm, respectively.

Fig. 5 illustrates the experimental setup to evaluate the performance of the all four MPPT algorithms. The

Fig. 4. Simulation circuit for MPPT control.
constant voltage control method is the simplest control method, which keeps the array near the MPP by regulating the array voltage and matching it to a fixed reference voltage. This method starts from the assumption that any variations in the insolation and temperature of the array are insignificant and that the constant reference voltage is an adequate approximation of the true maximum power point. Even though it neglects the effect of the insolation and temperature of the solar array, it is more effective at low insolation than both the P&O method and the IncCond method.

The P&O algorithms are widely used in MPPT because of their simple structure and the few measured parameters required. They operate by periodically perturbing (i.e. incrementing or decrementing) the array terminal voltage and comparing the PV output power with that of the previous perturbation cycle. If the power is increasing the perturbation will continue in the same direction in the next cycle, otherwise the perturbation direction will be reversed. This means the array terminal voltage is perturbed every MPPT cycle; therefore when the MPP is reached, the P&O algorithm will oscillate around it resulting in a loss of PV power, especially in cases of constant or slowly varying atmospheric conditions. This problem can be solved by improving the P&O algorithm’s logic for comparing the
parameters of two preceding cycles. If the MPP is reached, the perturbation stage is bypassed (Sullivan and Powers, 1993). Another way to reduce the power loss around the MPP is to decrease the perturbation step, however, the algorithm will be slow in following the MPP when the atmospheric conditions start to vary and more power will be lost. In cases of rapidly changing atmospheric conditions, as a result of moving clouds, it was noted that the P&O MPPT algorithm deviates from the MPP due to its inability to relate the

Fig. 7. Simulation result of constant voltage control method.

Fig. 8. Simulation result of P&O MPPT control method.
change in the PV array power to the change in the atmospheric conditions. The perturbation step size is determined to be 0.1 in this simulation of the MPPT algorithm for all cases.

On the contrary, the array terminal voltage is always adjusted according to its value relative to the MPOP voltage in the IncCond algorithm. The basic idea is that at the MPP the derivation of the power with respect to the voltage vanishes because the MPP is the maximum of the power curve. Since the IncCond method offers good performance under rapidly changing atmospheric conditions, contrary to the P&O method, it is widely used in various applications (Hua and Shen, 1998).

Finally, a novel two-mode MPPT control algorithm which combines the constant voltage control at less than 30% normalized insolation intensity and the IncCond method at more than 30% normalized insolation intensity is proposed to improve efficiency of the 3 kW PV power generation system at different insolation conditions. Fig. 6 shows the flowchart of the proposed two-mode MPPT algorithm.

4. Simulation results and experimental evaluation

Both the steady-state and transient characteristics of each control algorithms along with its measured efficiency are analyzed, respectively. Figs. 7–9 show the simulation results of each MPPT algorithms due to the step variations of insolation. From the above figures, tracking errors of 0–30 W are occurred in the constant voltage control compared with those of 0–2 W in the P&O method and those of 0–1.5 W in the IncCond method. The IncCond method is superior to the other method in following MPP of the system.

The results are listed at Table 2, which shows that the IncCond method provides better efficiency at more than 30% insolation intensity, but it only provides less than 35% efficiency at 20% insolation intensity. However, the constant voltage control method at less than 30% normalized insolation intensity is much more efficient than other cases. Figs. 10 and 11 show the inverter output voltage waveforms of the proposed two-mode MPPT control at insolation step changes, decreasing from 75% to 25% and

<table>
<thead>
<tr>
<th>Insolation (W/m²)</th>
<th>Experimental data (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Constant voltage MPPT</td>
</tr>
<tr>
<td>100</td>
<td>96.6</td>
</tr>
<tr>
<td>80</td>
<td>96.5</td>
</tr>
<tr>
<td>60</td>
<td>96.3</td>
</tr>
<tr>
<td>40</td>
<td>96.5</td>
</tr>
<tr>
<td><strong>30</strong></td>
<td><strong>96.5</strong></td>
</tr>
<tr>
<td>20</td>
<td>96.4</td>
</tr>
<tr>
<td>10</td>
<td>38.9</td>
</tr>
</tbody>
</table>

Table 2: MPPT efficiency characteristics at different insolation intensity.

Fig. 9. Simulation result of IncCond MPPT control method.
increasing from 25% to 75%, respectively. Experimental results show that the proposed two-mode MPPT control shows excellent performance at less than 30% insolation intensity. This is the reason why the proposed MPPT control is required at lower insolation level. Especially, in case solar insolation changes rapidly at lower insolation, P&O and IncCond MPPT control method fail to track MPP. However, the proposed two-mode MPPT control algorithm works very well due to the adoption of the modified constant voltage control method.

Fig. 10. Inverter output waveforms at insolation step decrease from 75% to 25%.

Fig. 11. Inverter output waveforms at insolation step increase from 25% to 75%.
5. Conclusions

In this paper, the effectiveness of the three different control algorithms is investigated via simulations and the proposed efficiency evaluation method on experiment. Both the steady-state and transient characteristics of each control algorithms along with measured efficiency are analyzed. Finally, a novel two-mode MPPT control algorithm combining the modified constant voltage control and IncCond method is proposed to improve efficiency of the 3 kW PV power generation system at different insolation conditions.

Actually, total six 3 kW PV systems and supervisory control and data acquisition (SCADA) system are constructed for analyzing performance of PV system at demonstration field test center of Gwang-Ju in Korea. As climatic and irradiation conditions are varied, operation characteristics of the PV system are collected and analyzed in data-acquisition system. As a result, the IncCond-method provided less efficiency at less than 30% \( (S > 250 \text{ W/m}^2) \) normalized insolation intensity for the PV system at site. On the contrary, the modified constant control method is much more efficient on that condition. Therefore, arbitrary insolation intensity can be chosen depending on site, where the PV system has been installed.

Mentioned experimental results show that the proposed two-mode MPPT control provides excellent performance at less than 30% insolation intensity, covering whole insolation intensity without additional hardware circuitry.

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