An advanced incremental conductance MPPT technique considering time-varying solar irradiances

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Abstract. For most of Maximum Power Point (MPP) Tracking (MPPT) techniques, their design principle are based only on output characteristics of photovoltaic (PV) panel under steady state, i.e., under constant solar irradiance. Because this steady state output characteristics do not describe how the operating point moves between different I-V curves under dynamic state, i.e., under varying solar irradiance, it inevitably results in poor dynamic performances or wrong perturbations. Focusing on this issue, in this paper, we propose the concepts of output characteristics of PV system which consist of two parts: output characteristics of PV system under steady state and output characteristics of PV system under dynamic state. Building on the output characteristics of PV system under two states, the widely used Incremental Conductance (Inc.Cond) technique is modified. Through simulation studies and the conventional Inc.Cond technique, the proposed advanced Inc.Cond technique retains good performances under steady state; under dynamic operation states, the MPPT performances are significantly improved.

1. Introduction
Solar PV power generation has been widely applied in practice, exerting substantial economic, social and environmental benefits. Because of its lower photoelectric conversion efficiency, high-efficiency power generation techniques for PV system are urgently needed. MPPT techniques are one of techniques to improve the generation efficiency for PV system [1-3]. Reference [4-6] has a comprehensive summary for all kinds of MPPT techniques. The widely-used MPPT techniques are Perturbation and Observation (P&O)/hill climbing and Incremental Conductance (Inc.Cond) [7-9]. Nowadays, the research trend is focused on the intelligent method based MPPT techniques, e.g., fuzzy logic, neural networks and Genetic Algorithms (GA) [10-13]. Among all MPPT techniques, Inc.Cond technique has been widely employed in practice because of its simplicity, economy and effectiveness [14, 15]. However, under the condition of continuously varying solar irradiances, poor dynamic responses happen with either fixed step-size or variable step-size [16-19]. In order to eliminate the poor dynamic performances, both the output characteristics of PV system consist of the steady state output characteristics and the dynamic state output characteristics in [20] must be investigated, instead of the only steady state output characteristics. Authors in [20] discussed the reasons for poor dynamic performances under varying solar irradiance. Based on the steady state output characteristics and the dynamic state output characteristics of PV systems, a novel high-efficiency power generation MPPC technique was proposed in [20]. In this paper, based on the output characteristics under two states, the conventional Inc.Cond technique is modified and branded as an advanced Inc.Cond technique. Specifically, at first, a judgment for the
incremental conductance $\Delta G$ is proposed to distinguish whether the PV system operates under steady state or dynamic state. Secondly, the proposed advanced Inc.Cond technique consists of two parts: (1) under steady state, the conventional Inc.Cond technique with variable step-size is still adopted; and (2) under dynamic state, the algorithm of Adaptive Voltage Tracking (AVT) is proposed to track the MPP. Through simulation comparisons, the advanced Inc.Cond technique shows the advantages over the conventional Inc.Cond technique and the performances under dynamic state are significantly improved.

The rest of the paper is organized as follows. In Section 2, the concepts of the steady state and dynamic state output characteristics for PV system are proposed and analyzed. The design principles for conventional and advanced Inc.Cond technique are presented in Section 3. The simulation results of the output characteristics under steady response and dynamic response are compared in Section 4. Finally, the paper concludes in Section 5.

2. Analysis for output characteristics of PV system

In this section, first of all, the concept of the steady state and dynamic state output characteristics for PV system are depicted. The studied PV system is shown in Figure 1 which consists of a PV array, DC/DC converter, load and MPPT controller, where the relevant parameters of the PV system are adopted from [20]. The output characteristics of PV system are investigated under closed-circuit conditions.

2.1 Output characteristics for PV system under closed-loop circuit

Because PV panels have a relatively high thermal inertia, the temperature on the PV panel surface changes slowly, and the open circuit voltage $V_{oc}$ changes slowly as well. Therefore, when the effect of temperature variations on solar panel is indirectly considered, the output characteristics for PV panel only have direct relationship with solar irradiance $S$ and load $R_{in}$ [20].
When the solar irradiance is constant and load varies, or under steady state, the I-V curves and P-V curves of PV panel are shown in Figure 2, which is defined as the steady-state output characteristics for PV system. When the solar irradiance varies and load is constant, or under dynamic state, the I-V curves and P-V curves of PV panel are shown in Figure 3, which is defined as the dynamic-state output characteristics for PV system. Obviously, the steady-state output characteristics and the dynamic-state output characteristics are invariably different. Therefore, focusing on different operating states, two control strategies are respectively taken.

2.2. Further analysis for the output PV characteristics

![Figure 4. The characteristics of PV panel under constant solar irradiance](image)

![Figure 5. The characteristics of PV panel under varying solar irradiances](image)

Most of MPPT techniques are based only on the P-V curves under steady state without considering dynamic state. Under steady state, the output characteristics of PV panel are shown in Figure 4. The blue line is the P-V curve. The red line is P'-V curve, where P' = ∆P/∆V. For P-V curve, obviously, an extreme point (MPP) exists. For P'-V curve, when P' = 0, P' > 0 and P' < 0, the operating point operates at MPP, left to MPP and right to MPP, respectively. These features are used to design the control strategy to find MPP under steady state.

Under dynamic state, the output characteristics of PV panel are shown in Figure 5. The blue line represents the P-V curve, P = V²/ R_{in}. The red line is P'-V curve, P' = 2V / R_{in}. Obviously, no extreme point exists for P-V curve and P'-V curve. Under this dynamic state, no outstanding characteristics can be regarded as control basis.

3. The design principles for the conventional and the advanced Inc.Cond technique.

3.1. Design principle for the conventional Inc.Cond technique.

The conventional Inc.Cond technique is based on Figure 4.

\[
\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V \frac{dI}{dV} \approx I + V \frac{\Delta I}{\Delta V}
\]  

(1)

When the operating point is at MPP,

\[
\frac{\Delta I}{\Delta V} = -\frac{I}{V}
\]

(2)

When the operating point is left to MPP,

\[
\frac{\Delta I}{\Delta V} > -\frac{I}{V}
\]

(3)
When the operating point is right to MPP,
\[ \frac{\Delta I}{\Delta V} < -\frac{1}{V} \]  
In (2-4), \( \Delta I/\Delta V \) and \( I/V \) represent the incremental conductance and instantaneous conductance, respectively. They describe the mathematical relationship for Figure 2 in the I-V plane.

**Figure 6.** Flowchart of the conventional Inc.Cond. algorithm (only considering constant solar irradiance)

Based on (2-4), the typical flowchart of the Inc.Cond technique is shown in Figure 6 which is based on the characteristics under steady state shown in Figure 4 without considering the characteristics under dynamic state shown in Figure 5.

In Figure 6, the control options of the Inc.Cond technique are analyzed as follows.
(a) \( \Delta V(k) = 0 \) is set. It is adopted to eliminate the illegal calculation when the denominator \( \Delta V(k) \) equals zero in (2-4). When \( \Delta V(k) = 0 \) and \( \Delta I(k) = 0 \), \( D(k+1) = D(k) \). It is adopted to eliminate the steady state oscillations.
(b) When \( \Delta V(k) = 0 \) and \( \Delta I(k) \neq 0 \). Its control options are designed as follows.
   - If \( \Delta I(k) > 0 \), \( D = D - D.D \).
   - If \( \Delta I(k) < 0 \), \( D = D + D.D \).
   This option is not always correct at least for the following three cases when \( \Delta V(k) = 0 \).
   Case 1: PV system operates on MPP. When solar irradiance has slight changes and \( \Delta V(k) = 0 \), this control strategy is correct.
   Case 2: When load has slight changes with constant solar irradiance and \( \Delta V(k) = 0 \), the above control strategy is wrong. They must be modified as \( D = D - D.D \) when \( \Delta I(k) > 0 \), and \( D = D + D.D \) when \( \Delta I(k) < 0 \).
   Case 3: When the two sampling points operates on the droop line of P-V curve, \( \Delta V(k) = 0 \) is easily produced. The control option must be \( D = D + D.D \) under both steady state and dynamic state. Therefore, in Figure 6, the default control option will cause wrong perturbations when \( \Delta V(k) = 0 \) and \( \Delta I(k) \neq 0 \).
(c) When \( \Delta V(k) \neq 0 \), the control strategy follows the conventional Inc.Cond technique for (2-4) and it is correct under steady state. However, wrong perturbations will happen under dynamic state.
3.2. The conventional Inc.Cond technique with variable step-size $\Delta D$

Generally, the perturbation $\Delta D$ is set as follows,

$$\Delta D = N_1 \left| \frac{\Delta P}{\Delta V} \right|$$  \hspace{1cm} (5)

where $N_1$ is a scaling factor. $\Delta P = P(k) - P(k-1)$, $\Delta V = V(k) - V(k-1)$ and $\Delta D = D(k-1) \pm \Delta D$.

As shown in Figure 7, obviously, $\Delta D$ varies with the external conditions. Under steady state, $\Delta D$ follows the blue line, and $\Delta D \approx 0$ when $V = V_m$. $\Delta D$ follows the red line under dynamic state, and $\Delta D$ has significant large value, $\Delta D = N_1(2V/R_{in})$, when $V = V_m$. Therefore, equation (5) is correct as the control strategy under steady state, but not under dynamic state.

3.3 Design principle for the advanced Inc.Cond technique

![Image](flowchart.png)

*Figure 8. Flowchart of the proposed advanced Inc.Cond technique algorithm (considering both constant and varied solar irradiances)*
In order to maintain the advantages from the conventional Inc.Cond with variable step-size and prevent significant fluctuations under dynamic state, in this section, an advanced Inc.Cond technique is proposed as shown in Figure 8, which consists of two parts: the conventional Inc.Cond technique with variable step-size is adopted under steady state, and the algorithm of tracking $V_m$ is adopted under dynamic state. The modifications are detailed as follows.

(1) Setting $V_m = 0$:
   When $V_m = 0$, MPP is tracked by the conventional Inc.Cond technique with variable step-size. This is, the control principles are almost same for Figure 8 with Figure 6. Once $V_m \neq 0$, the function of this setting is ended.

(2) Setting $\Delta G > 0$: It is adopted to distinguish between steady state and dynamic state.
   If $\Delta G > 0$, the PV panel operates under dynamic state.
   If $\Delta G < 0$, the PV panel operates under steady state.

(3) When $\Delta G > 0$, because the value of $V_m$ almost keeps constant in a defined time, the algorithm of tracking $V_m$ is designed to track MPP. This is a more stable MPPT method under various operating conditions.
   If $V(k) < V_m$, that is, the operating point is on the left of MPP, then, $D = D - \Delta D_2$. $\Delta D_2$ is set as follows.
   
   \[
   \Delta D_2 = N_2 \left| \frac{V_m - V_k}{V_m} \right| \tag{6}
   \]
   where $0 < \Delta D_2 < N_2$. $N_2$ is the scaling factor which is set as 0.05 to meet the control requirements.

   If $V(k) > V_m$, that is, the operating point is on the right of MPP, then, $D = D + \Delta D_3$. $\Delta D_3$ is set as follows.
   
   \[
   \Delta D_3 = N_3 \left| \frac{V_k - V_m}{V_{oc} - V_m} \right| \tag{7}
   \]
   where $0 < \Delta D_3 < N_3$. $N_3$ is the scaling factor which is set as 0.05 to meet the control requirements.

   Obviously, $\Delta D_2$ and $\Delta D_3$ are two controllable variables.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig9.png}
\caption{Figure 9. $S = 1000 \text{ W/m}^2$ and $R$ has a step change.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig10.png}
\caption{Figure 10. $S = 1000 \text{ W/m}^2$ and $R$ has a ramp change.}
\end{figure}
(4) When $\Delta G < 0$, the conventional Inc.Cond technique with variable step-size is adopted to track MPP. Furthermore, three modifications for it are implemented as follows.

(4.1) $\Delta G + G = 0$ is modified as $|\Delta G + G| \leq E$, where $E$ represents the small marginal error. Here, the value of $E$ must be larger than zero in order to increase the probability to capture MPP. On the other hand, the value of $E$ should be small as much as possible in order to track an accurate MPP. In this paper, $E = 0.4\%$.

When the sampled point operates under the condition of $|\Delta G + G| \leq E$, this current point is regarded as MPP, $V_m = V(k)$ and $D = D$. $V_m$ is found or updated by this setting. The perturbation $\Delta D_1$ follows (5). Generally, its value range is shown in Figure 7. Especially, when it operates under varying solar irradiance and varying load, its value will be $[0, +\infty]$ with respect to voltage from 0 to $V_{RMargin}$. Obviously, $\Delta D_1$ is an uncontrollable variable under dynamic state. Therefore, a supplementary judgment is required to (4.2) and (4.3).

(4.2) If $\Delta G + G > 0$, an supplementary judgment from the direction of $V(k) - V_m$ is applied.

(4.2.1) If $V(k) - V_m > 0$, the algorithm of tracking $V_m$ is applied and $D = D + \Delta D_3$.

(4.2.2) If $V(k) - V_m < 0$, a supplementary judgment is applied to compare the magnitude between $\Delta D_1$ and $\Delta D_2$.

If $\Delta D_1 < \Delta D_2$, the conventional Inc.Cond technique is applied and $D = D + \Delta D_1$.

If $\Delta D_1 > \Delta D_2$, the algorithm of tracking $V_m$ is applied and $D = D - \Delta D_2$.

(4.3) If $\Delta G + G < 0$, a supplementary judgment from the direction of $V(k) - V_m$ is applied.

(4.3.1) If $V(k) - V_m < 0$, the algorithm of tracking $V_m$ is applied and $D = D - \Delta D_2$.

(4.3.2) If $V(k) - V_m > 0$, a supplementary judgment is applied to compare the magnitude between $\Delta D_1$ and $\Delta D_3$.

If $\Delta D_1 < \Delta D_3$, the conventional Inc.Cond technique is applied and $D = D + \Delta D_1$.

If $\Delta D_1 > \Delta D_3$, the algorithm of tracking $V_m$ is applied and $D = D + \Delta D_3$.

(5) $\Delta V(k) = 0$ & $\Delta I(k) = 0$ is remained to eliminate the steady state oscillations. When $\Delta V(k) = 0$ & $\Delta I(k) \neq 0$, the tracking process is modified as (3).
Figure 13. The zoom-in power for Figure 11 when $S$ has an increasing step change

4. Comparison of simulation results
Simulation comparison is carried out between the conventional Inc.Cond technique with variable step-size marked in blue line and the proposed Inc.Cond technique for red line shown in Figure 9 to Figure 12. Their responses are nearly identical from Figure 9 to Figure 11, where they operate under steady state. However, when solar irradiance has an increasing step change in Figure 11, one wrong perturbation exists marked in blue line for conventional technique, but not for the proposed Inc.Cond technique, and its details are shown in Figure 13. In Figure 12, it is clear that the system response with the proposed Inc.Cond technique has a significant improvement over the conventional one under dynamic operation state, and wrong perturbations are also prevented with the proposed method.

5. Conclusion
The simulation results demonstrate that the proposed advanced Inc.Cond technique retains satisfactory steady state performances and the dynamic state performances are significantly improved without fluctuations. It is proved again that the output characteristics of PV system contain both the steady state output characteristics and the dynamic state output characteristics, which ought to be considered when designing MPPT strategies. For I-V curves, their slopes ($\Delta G$) can be conditionally regarded as the judgment to distinguish steady state and dynamic state.

6. References
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