Extremum Seeking Control Based Integration of MPPT and Degradation Detection for Photovoltaic Arrays

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Abstract—Regarding the reduction of the cost of energy (COE) for photovoltaic (PV) systems, two important issues are maximizing the efficiency of power generation and fault diagnosis. This study presents an integrated framework that achieves both maximum power point tracking (MPPT) control and diagnosis of change in internal resistance simultaneously. An extremum seeking control (ESC) strategy is developed to maximize the power output of the PV array by regulating the voltage input to the DC–DC converter. Simulation results show that the ESC can achieve MPPT with periodic dither signals such as sinusoidal or square-wave signals. The degraded PV cells often demonstrate certain change of internal resistance, i.e. increase in the series resistance and decrease in the shunt resistance. The change of these internal resistances can induce the change of transient behavior of the dithered output remarkably for square wave dithering, which is validated with simulation study. The ESC with square-wave dithering can thus provides the dual benefits of MPPT and degradation detection simultaneously. Furthermore, simulation study on the PV modules under partial shading, though the P-V characteristic has changed, the proposed option is to pick the optimal regions to narrow down the ESC searching intervals and thus can locate the global maximum power point faster.

I. INTRODUCTION

Solar energy can be captured as a renewable energy source via photovoltaic (PV) or solar thermal systems. A PV system directly converts sunlight into electricity. The basic unit of PV system is the PV cell. PV cells can be grouped in parallel and/or series to form PV modules or arrays. The I-V and P-V curves of the PV arrays have nonlinear characteristics that are dependent on irradiance intensity, temperature and the PV degradation. At each irradiance level, there exists a unique point with the maximum power output (MPP) [1]. Figure 1 shows a typical P-V characteristic curve, and the MPP appears on the top of the curve peak with \( V = V_{mpp} \). A major disadvantage for the PV system is the relatively higher cost of energy (COE), compared to the conventional power generation and even other renewable sources such as wind. Maximizing the efficiency of power output is thus critical for operating the PV systems. Realization of MPPT on PV systems can be achieved via regulating the PV terminal voltage, i.e. the input voltage to the converters, with certain control algorithms.

There have been many algorithms developed for MPPT, e.g. the look-up table (LUT) method, the voltage/current based PV generator method, the perturbation-and-observe method, the incremental conductance method, the fuzzy logic control and the extremum seeking control (ESC) method. The LUT method is to compare the measured value of PV generator’s voltage and current with the predetermined data. A proportional-integral (PI) controller is often used to adjust the duty cycle of DC–DC converter [2]. The PI controller can achieve perfect tracking in steady state and also reject the effect of disturbance in irradiation or load so that the system can be maintained at the optimal predetermined operating point. One drawback of LUT method is inability to adapt the LUT to the variation in panel characteristics and degradation. Another drawback is the requirement for large memory capacity. The Voltage/Current based PV Generator Method [3] is based on the linearly proportional property of MPP to its open-circuit voltage or short-circuit current. This method requires the measurement of \( V_{oc} \) and \( I_{sc} \), and the operating voltage/current can be adjusted according to the equation. This process is repeated periodically. This method is simple and economical, but the downtime power loss is significant due to scanning the entire control range off line. Selection of \( K_1 \) and \( K_2 \) is not easy because of manufacturing inconsistency and device degradation over time.

The most commonly used method in practice so far is the Perturbation and Observe (“P&O”) Method. It is an iterative method of obtaining MPP [3]. It perturbs the operating point of PV generator and decides the change in input based on the measured PV array characteristics. The MPP is reached when \( \frac{dP}{dV} = 0 \). The array terminal voltage is perturbed at every cycle. Hua and Chen [4] described the Incremental and Conductance Method based on the idea that MPP is obtained...
where the derivative of the power with respect to the voltage vanishes, i.e. \( dP/dV=0 \) at the MPP, \( dP/dV>0 \) to the left of MPP, and \( dP/dV<0 \) to the right of the MPP. The algorithm was derived by expanding the power derivative via \( dP/dV=d(I)V/dV=I+VdI/dV \), so that the equivalent conductance vanishes at MPP. Fuzzy Logic is another method to track MPP [5]. It has the advantage of robustness and simplicity, does not require the knowledge of the exact model, however, needs the complete knowledge of the operation of PV system. The system operation is based on sets of predetermined rules.

The extremum seeking control (ESC) is a nearly model free self-optimizing control strategy that can search for the unknown and/or time varying optimal input parameter regarding a given performance index of a nonlinear plant process [21]. Leyva et al. [31] presented a work which is a classic extremum seeking control (ESC) algorithm described in Blackman’s monograph in early 1960’s [21], and supplied a stability proof via Lyapunov method. The MPPT is achieved by closing the search loop with the integrator. In this study, we have followed an alternative path of ESC for PV MPPT, based on the dither-demodulation framework described in [20,22,23] Such ESC scheme relies on the use of a pair of dither and demodulation signals, along with high-pass and low-pass filters, to extract gradient information. Similar to the method in Leyva et al. [31], closing the control loop with an integrator can drive the gradient towards zero in steady state, which achieves the optimality. As the gradient information is locked to the particular dither frequency, this ESC scheme is more robust to the process noise and temporal variation of the performance map, compared to the classic ESC methods without dithering signals [21]. This ESC method has successful applications in various systems such as axial flow compressors, jet engines, combustion, HVAC, wind turbine among others [26,27,28]. For the dither-demodulation scheme, one advantage is that the gradient information is carried by the dither harmonic, with which it is more robust against measurement noise and change in performance map. Another advantage is that particular dither action such as square wave provides transient information that can be used for fault detection.

In addition to the efficiency of power generation, another big issue for PV system operation is the reliability. As PV systems are more expensive in terms of cost per unit power, it is beneficial to extend the life span of the PV panels as long as possible and to reduce the operation and maintenance (O&M) cost[6][7]. Long period of time exposure in the outdoors environment leads to degradation of PV systems. Degradation may include degradation of packaging materials, loss of adhesion, degradation of cell/module interconnects, degradation caused by moisture intrusion, degradation of the semiconductor device [8], decoloration, cracked cells, hot spot formation, shunt paths [9]. Although the change of the internal resistances can be identified via offline measurement with certain instruments, it is more desirable to detect such change online to eliminate the downtime cost. Furthermore, it is desirable to develop detection schemes without using any additional sensors.

In this study, we propose a detection scheme for identifying the change in internal resistance by taking advantage of the special feature in the ESC with square-wave dither signals. It will be demonstrated later in the paper that the rise time of the dithered output varies with the internal resistances of the PV system. Such schemes does not require any addition sensor, which provides a cost-effective measure for achieving both MPPT and fault detection. As this approach takes advantage of existing signals of ESC, we consider it an “ESC integrated” detection scheme.

The remainder of this paper is organized as follows. Section II reviews the PV modeling and presents the simulation results for static P-V and I-V characteristics for PV array and for shading effects. A design of DC-DC converter is presented in Section III, which is the voltage regulation unit for MPPT. The ESC algorithm is overviewed and Simulation results are presented in Section IV, followed by the ESC integrated detection of change in internal resistance in Section V. The paper is finally concluded in Section VI.

II. PHOTOVOLTAIC SYSTEM MODELING

A. Ideal Single Cell

The equivalent circuit of an ideal PV cell is shown as the dashed box in Fig. 2. The basic equations for describing the I-V characteristic of the ideal PV cell are [10]

\[
I = I_{PV_{cell}} - I_{O_{cell}} [\exp(\frac{qV}{akT}) - 1] 
\]

\[
I_{O_{cell}} [\exp(\frac{qV}{akT}) - 1] = I_d \tag{1b}
\]

where \( I_{PV_{cell}} \) is the current generated by the incident light that is proportional to the irradiation, \( I_{O_{cell}} \) is the reverse saturation or leakage current of the diode, \( q \) is the electron charge with the value of \( 1.60217646 \times 10^{-19} \) Columb, \( k = 1.3806503 \times 10^{-23} \) J/K is the Boltzmann constant, \( T \) is the temperature of the p-n junction, and \( a \) is the diode ideality. In particular, Eq. (1b) is known as the Shockley diode equation. Note that the model in Eq. (1) does not include the equivalent internal resistances \( R_P \) and \( R_S \).

![Fig. 2. PV Cell Equivalent Circuit with Single Diode](image)

B. Array Modeling

Equation (1) represents the behavior of a single cell, which is not enough for characterizing a PV array. The PV array consists of a number of inter-connected cells, either in parallel, or series, or the combination of both. To obtain the characteristics of PV arrays, Equation (1a) is enhanced into the following formulation with additional parameters [10]
where $I_{PV}$ and $I_o$ are the photovoltaic and saturation currents of the array, respectively, and $V_T = N_e k T / q$ is the thermal voltage of the array with $N_e$ cells connected in series. The total voltage for $N_e$ cells in series is $N_e V_T$. Cells connected in parallel increase the current, and $R_s$ and $R_P$ are the equivalent series and shunt resistances of the array, respectively. Compared to Eq. (1b), Eq. (2) is the single-diode model for a PV array. Some multi-diode models have been proposed for higher accuracy and other purposes [11-15]. This study has adopted the single diode model in Eq. (2) [10].

Figure 3 illustrates the $I-V$ curve characteristic of a PV array. Before the MPP point, it can be approximated as a current source, while beyond this point, it is roughly a voltage source [10]. Series resistance $R_s$ has stronger influence when the device operates in the voltage source region, while parallel resistance $R_P$ has stronger influence in the current source region of operation. The assumption $I_{SC} ≈ I_{PV}$ is generally used in PV models because. In practical devices, $R_s$ is low and $R_P$ is high. The light induced current of the PV cell depends linearly on the solar irradiation and is also influenced by the temperature according to

$$I_{PV} = (I_{PV,s} + K_s T) \frac{G}{G_n}$$

where $I_{PV,s}$ is the light-induced current under the nominal condition ($T_n = 25°C$ and $G_n = 1000$ W/m²) and $\Delta T = T - T_n$.

The diode saturation current $I_o$ and its dependence on the temperature can be expressed as

$$I_o = I_{o,n} \left[ \frac{T_n}{T} \right] \exp \left[ \frac{q E_g}{a k} \left( \frac{1}{T} - \frac{1}{T_n} \right) \right]$$

where $E_g$ is the bandgap energy of the semiconductor ($\approx 1.12$ eV for polycrystalline silicon at 25°C) [10]. $I_{o,n}$ is the nominal saturation current, which can be expressed as

$$I_{o,n} = \frac{I_{SC,n}}{\exp \left( \frac{V_{OC,n}}{a V_{T,n}} \right) - 1}$$

where $V_{OC}$ is the thermal voltage of $N_e$ series connected cells at the nominal temperature $T_n$. Estimation of diode constant $a$ was studied by Carrero et al. [16] and Walker [17]. The value of $a$ is often chosen between 1 to 1.5, depending on other parameters of the $I-V$ model. The diode constant affects the curvature of the $I-V$ characteristic, and slight improvement in modeling accuracy is possible by parameter tuning. As a further improvement, Eq. (4) can be replaced by

$$I_o = \frac{I_{SC,a} + K_v \Delta T}{\exp \left( \frac{V_{OC,a} + K_v \Delta T}{a V_T} \right) - 1}$$

where $K_v$ and $K_f$ are the current and voltage coefficients, respectively. Such improvement is to match the open circuit voltage with the experimental data for an extended range of temperatures. Also, series resistance $R_s$ and parallel resistance $R_P$ should be calculated appropriately. The current at maximum power point, which can be assumed as the current source of the equivalent circuit $I_o = I_{PV} - I_J$. In general, a PV array consists of both series and parallel connected PV cells, with $N_s$ being the number of series connected cells and $N_{pp}$ as that of parallel connected cells, respectively.

C. Simulation

The PV array modeling and ESC are simulated in Simulink and SimPowerSystems. The PV array for simulation study is a 15 x 2 modules array and each module is 54 cells in series connection. The equivalent circuits and the associated equations are encapsulated in the subsystem of PV cell array. For the PV array, both temperature and irradiance are set at the nominal values, i.e. 25°C and 1000 W/m², respectively. The nominal internal resistances are $R_s = 322 \Omega$ and $R_P = 0.075 \Omega$. Figures 4 and 5 compare the P-V and I-V characteristics, respectively, under different choices of internal resistance values. The dashed line is for $R_p = 450 \Omega$, $R_s = 1 \Omega$, and the dotted line is for $R_p = 200 \Omega$ and $R_s = 1 \Omega$.
III. DC-DC CONVERTER

DC-DC converter is widely used for PV systems, e.g. typically for battery storage. In order to achieve MPPT, the input voltage of the DC-DC converter is controlled for the PV array to achieve its MPP. Since the converter output voltage $V(t)$ is a function of switching duty cycle $D$ of the pulse-width modulator (PWM), a control system can be constructed that varies the duty cycle to regulate the output voltage of PV array to follow a given reference $V_r$ [18].

DC-DC converters are categorized into buck, boost and buck-booster types. Choice of DC-DC converter depends on the change of voltage levels. In this study, a buck converter is designed to fit the voltage requirement on the load. The typical buck converter works based on the use of an electronic switch. A MPPT scheme, for which a buck converter is designed to fit voltage step-down was selected to illustrate the proposed system design, the PV output voltage can be regulated close to the reference voltage $V_{ref}$. With proper system design, the PV output voltage is corrupted by noise $n(t)$. The perturbed output is manipulated to obtain the gradient of the unknown and/or time-varying cost function $k(t, u)$, where $u(t)$ is the input parameter vector. Figure 8 shows the block diagram for a typical ESC system [19]. The measurement of cost function $k(t, u)$, is corrupted by noise $n(t)$. $F(s)$ and $F_d(s)$ denote the input and output dynamics, respectively. The dithering and demodulating signals are $d_i(t) = [a_i \sin(\omega_1 t + \alpha_i) \ldots a_m \sin(\omega_{m} t + \alpha_m)]$ and $d_{i}'(t) = [\sin(\omega_1 t) \ldots \sin(\omega_{m} t)]$, respectively, where $\omega_i$ are the dithering frequencies for each input parameter channel, and $\alpha_i$ are the phase angles introduced intentionally between the dithering and demodulating signals, for $i = 1, \ldots, m$. The ESC is used to construct a MPPT for the PV system, i.e. finding the optimizing input $u_{opt}(t)$ for the unknown and/or time-varying cost function $k(t, u)$, where $u(t)$ is the input parameter vector. Figure 8 shows the block diagram for a typical ESC system [19]. The measurement of cost function $k(t, u)$, is corrupted by noise $n(t)$. $F(s)$ and $F_d(s)$ denote the input and output dynamics, respectively. The dithering and demodulating signals are $d_i(t) = [a_i \sin(\omega_1 t + \alpha_i) \ldots a_m \sin(\omega_{m} t + \alpha_m)]$ and $d_{i}'(t) = [\sin(\omega_1 t) \ldots \sin(\omega_{m} t)]$, respectively, where $\omega_i$ are the dithering frequencies for each input parameter channel, and $\alpha_i$ are the phase angles introduced intentionally between the dithering and demodulating signals, for $i = 1, \ldots, m$. The perturbed output is manipulated to obtain the gradient of the cost function $k(t, u)$. These signals work in conjunction with the high-pass filter $F_{hp}(s)$, the demodulating signal and the low-pass filter $F_{lp}(s)$, to produce a signal proportional to the gradient of the cost function at the input of the multivariable integrator. By integrating the gradient signal, asymptotic stability of the closed-loop system will make the gradient vanish, i.e. reaching the optimum. Compensator $K(s)$ may improve the transient performance by compensating the input/output dynamics.

IV. EXTREMUM SEEKING CONTROL

A. ESC Overview

There was great interest in ESC in the 1950s and 1960’s [20]. The research by Krstić and his coworkers in the past decade ignited a resurgence of ESC [21, 22]. Krstić and Wang provided the stability proof for general SISO nonlinear plants based on averaging and singular perturbation methods [21]. More design issues were addressed in another paper by Krstić [22]. Later, the stability proof was extended to discrete-time situation [23]. The proposed ESC framework has been applied to various applications, such as maximizing biomass production rate [24], maximizing pressure rise in axial flow compressor [25], minimizing acoustic pressure oscillation to enhance combustion stability [26], minimizing the power demand for air-handing units of building HVAC systems [27], and maximizing energy capture for wind turbine operation [28] [29], among others.

B. PV ESC Implementation

The ESC is used to construct a MPPT for the PV system, finding its intrinsic optimized power output at given value of temperature and irradiance.

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Fig. 6. Block Diagram of voltage control system with DC-DC buck converter, PI controller MOSFET and PWM

Fig. 7. Controlled PV output voltage
C. ESC Design

Typical ESC design needs to determine the following parameters [19]: the dither amplitude \(a\), the dither frequency \(\omega_d\) and phase \(\alpha\), the high pass filter \(F_{HP}(s)\), the low pass filter \(F_{LP}(s)\), and the dynamic compensator \(K(s)\). Based on averaging analysis, the dither frequency should be relatively large with respect to the adaptation gain, but should not be too large to trigger unmodeled dynamics and make the system more sensitive to measurement noise. Also, if the dither frequency is well out of the bandwidth of the input dynamics, the roll-off in the magnitude response will slow down the convergence. Therefore, dither frequency \(\omega_d\) is typically chosen to be just a moderate value smaller than the cut-off frequency of the input dynamics as long as it is enough to separate the time scales of the dither signal and the inner loop dynamics. Generally, the dynamic compensator should be designed based on the dither signal, adaptation gain and the frequency responses of the input dynamics. Particularly, a proper proportional-derivative (PD) action can increase the phase margin of the input dynamics and thus make the inner loop more stable. However, extreme values of the adaptation gain, especially the derivative gain, will make the system more affected by noise and thus destabilize the system. Further design guidelines are summarized as follows [19].

1) The dither frequency should be in the passband of the high pass filter and in the stopband of the low pass filter, and it should be below the cut-off frequency of the input dynamics of the respective channel.

2) The dither amplitude should be chosen to be sufficiently small to avoid large oscillation of output, and meanwhile sufficiently large to overcome the noise effect.

3) The dither phase angle should be chosen such that \(\theta = \angle F_{i}(j\omega) + \angle F_{HP}(j\omega) + \alpha \in (-\pi/2, \pi/2)\), and it is desirable to make \(\theta\) close to 0.

First, the time constant for the input dynamics is determined from the step response of the PV array power output as shown in the previous section. The time constant is estimated as \(T_i = 0.04\) sec. The dithering frequency is then selected as \(\omega_t = 15.7\) rad/sec. \(F_{HP}(s)\) and \(F_{LP}(s)\) were selected as

\[
F_{HP}(s) = \frac{22.21}{s^2 + 5.655s + 22.21}
\]

with the cut-off frequency chosen to be 0.3 times the dither frequency. The dither amplitude was chosen to be 0.5. To compensate for the phase lag and phase lead from the input dynamics and high pass filter \(F_{HP}(s)\), the dither phase angle \(\alpha\) was selected to be 0.7226 radian [19].

Simulation of the proposed ESC based MMPT is performed on Simulink. The open circuit voltage of the PV array is approximately 500V, and the short circuit current is 16.2A. The nominal condition with temperature at 298 K and irradiance of 1000 W/m² is adopted as the baseline scenario for the simulation. The simulation result is shown Fig. 10. First, the PV system is turned on and allows the system to operate for 1 second with 300 volts as voltage reference before turning on the ESC. The ESC output is settled at 423V, and the settling time was about 0.53 second.

V. ESC INTEGRATED DETECTION OF PV DEGRADATION

Figure 11 shows the ESC simulation results with square wave dither signal along with a zoomed view. When the square wave dither signal is used, the ESC output transient has rise time affected by the internal resistance changes. Therefore, the rise time of ESC dithering transient can be used to detect the change of internal resistance due to degradation. Figures 12 shows a case of comparing the ESC dithered transients with sinusoidal and square-wave dither signals for different internal resistance values. Table 1 summarizes the results for totally five cases of comparison. The square-wave dither signal is effective in detecting the change of internal resistances.
The simulation results demonstrate the potential for using the ESC dithered output rise time as a probe for detecting the change of internal resistance associated with the PV panel degradation. The change of parallel resistance $R_p$ has more impact on the output voltage, however, the change of series resistance $R_s$ affects the rise time more. Detection of PV degradation can be evaluated by further investigate the rise time of square wave dither signal.

Fig. 12. Comparison of ESC Dithered Outputs with Sinusoidal and Square-Wave Dither Signal with Nominal $R_p = 322 \, \Omega$ and $R_s = 0.07 \, \Omega$

Table I. Comparison of rise time for different $R_p - R_s$ values

<table>
<thead>
<tr>
<th>$R_p$ (Ω)</th>
<th>$R_s$ (Ω)</th>
<th>Rise Time (s) (Sine Dither)</th>
<th>Rise Time (s) (Square Dither)</th>
</tr>
</thead>
<tbody>
<tr>
<td>322</td>
<td>0.07</td>
<td>0.18</td>
<td>0.0125</td>
</tr>
<tr>
<td>200</td>
<td>0.07</td>
<td>0.18</td>
<td>0.008</td>
</tr>
<tr>
<td>100</td>
<td>0.07</td>
<td>0.18</td>
<td>0.007</td>
</tr>
<tr>
<td>322</td>
<td>1</td>
<td>0.18</td>
<td>0.007</td>
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<tr>
<td>322</td>
<td>3</td>
<td>0.18</td>
<td>0.006</td>
</tr>
</tbody>
</table>

VI. CONCLUSION

This study presents an integrated framework that can achieve maximum power point tracking (MPPT) and detection of PV array internal resistance simultaneously. An extremum seeking control (ESC) strategy is developed to maximize the power output of the PV array by regulating the voltage input to the DC-DC converter. Such ESC can work for periodic dither signals such as sinusoidal and square wave. The degraded PV cell is known to demonstrate change of internal resistance: increase in the series resistance and decrease in the parallel resistance. The change of the internal resistance can be identified from the transient of dithered output especially for square wave dithering. The ESC thus provides dual benefits of MPPT and degradation detection simultaneously. Partial shading illustrates different characteristics on $P-V$ curve with several local peaks, the ESC searching intervals can be narrowed down by picking the optimum regions. The size of such regions still needed to be further determined, future work will be based on it.

REFERENCES