Robust optimum design of maximum power point tracker for photovoltaic power generation systems

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Abstract. The photovoltaic array's power-voltage curve usually appears multiple peaks in the presence of partial occlusion and fault conditions, and the habitual maximum power point tracking (MPPT) algorithm is not easy to discover the MPP of the global space, thus falling into the local range, which extremely decreases the efficiency of the photovoltaic power generation system. In this paper, a robust optimum design technology employing an enhanced terminal attractor (ETA) and a monkey-king genetic algorithm (MKGA) are put forward. The proposed technology can be adopted for the maximum power point tracker of the photovoltaic power generation system, therefore yielding fast limited-time convergence and global extremum. The proposed photovoltaic power generation system is also implemented on the basis of Texas Instruments digital signal processor, to achieve the improvement of the tracking speed and good performance in the transient as well as steady-state. Simulation and experimental results have been provided to demonstrate the virtue of the proposed technology.

1. Introduction

For the sake of aggrandizing the efficacy of the photovoltaic (PV) power generation system, a maximum power point tracker (DC-DC converter with maximum power point tracking algorithm) has to be employed, and thus the PV array can yield the maximum power by adjusting the duty cycle of the DC-DC converter [1-5]. Different maximum power point tracking (MPPT) methodologies have been suggested in prior works [6-8]. Nevertheless, the PV array’s illuminance and surrounding temperature are interrelated to the change of the maximum power output in the PV panel. The above-mentioned MPPT algorithms may not provide the ability of fast tracking to MPPT, therefore decreasing power output. More precisely, a model can be approximated using piecewise linear MPPT method, but there are intricate mathematical calculations. The perturb and observe MPPT algorithm has been extensively adopted in PV MPPT because of its easiness, practicality and fewer measuring parameters. However, after reaching the PV MPP, the oscillation will occur at such point during continuous disturbed situations, causing PV loss in power. The shortcoming of intelligent fuzzy MPPT controller includes higher cost as well as greater complexity. The enhanced terminal attractor (ETA) delivers a finite time for the system state to converge, i.e. when there is uncertainty in the system perturbation, the system trajectory gets to the sliding-mode zone for sliding-mode locomotion in a definite time. Then it converges quickly to the balance point, and this method further strengthens the dynamical quality of the system [9-13]. However, PV arrays are susceptible to clouds, dust and other factors, causing partial shading or failure of the modules and the output power will appear at multiple regional extremes. Some approaches (such as greedy algorithm and ant colony optimization algorithm) tried to address multiple local extremum issues, but they were prone to stagnate on one particular solution, and the searching time is also long [14-15]. The monkey-king genetic algorithm (MKGA)
original form genetic algorithm is a bionic population intelligence optimization algorithm that simulates the development of biomechanical conventions to tackle sophisticated non-linear issues [16-20]. The monkey king is produced in monkey group competition, mainly relying on force conquer. The winner is the king with supreme power, and the loser is the slave. Therefore, it can be believed that the monkey-king genetic algorithm proposed in this paper is applied to enhanced terminal attractor for controlling the photovoltaic array under partial shielding or fault conditions, achieving global maximum power point tracking, which is absolutely a sensible and workable way. Both in the presence of partial shading or failure and uncertain nonlinearities, the results of the computer simulations and the digital signal processor-based implementation have illustrated that the proposed technology results in increased performance of the photovoltaic maximum power tracking system in the steady state and faster tracking in the transitory phase.

2. Dynamic modelling and control technology design
The equivalency circuitry for a solar cell can be plotted as Figure 1, where \( V_o \) indicates the output voltage, \( I_o \) represents the output current, \( R_{se} \) signifies the equivalence series resistance, \( R_{pa} \) denotes the equivalence parallel resistance, \( I_{pa} \) is the leakage current, \( I_d \) implies for the diode current, and \( I_{ph} \) is a current source.

![Equivalent circuit of single solar cell](image)

**Figure 1.** Equivalent circuit of single solar cell.

The output current of a single solar cell can be described as

\[
I_o = I_{ph} - I_{sat} \cdot (e^{q(V_o+I_o \cdot R_{se})/k_BT} - 1) - (V_o + I_o \cdot R_{se})/R_{pa}
\]

(1)

where \( q \) means the amount of charge contained in an electron, \( \kappa \) represents the ideal factor of a solar cell, \( K_B \) stands for Boltzmann constant, \( T_k \) denotes the absolute temperature, and \( I_{sat} \) indicates the reverse saturation current. The PV’s output power \( P_{pv} \) can be specified by letting the output current and the output voltage of the solar array as \( i_{pv} \) and \( v_{pv} \), respectively:

\[
P_{pv} = i_{pv} \cdot v_{pv} = \alpha \cdot I_{ph} \cdot v_{pv} - \alpha \cdot I_{sat} \cdot v_{pv} \cdot (e^{q \cdot v_{pv} / \kappa \cdot k_B \cdot T_k} - 1)
\]

(2)

where \( \alpha \) infers the number of solar cells connected in series and \( \beta \) is the number of solar cells connected in parallel. Thereafter the maximum power point appears as follows:

\[
\frac{\partial P_{pv}}{\partial v_{pv}} = 0 = i_{pv} + v_{pv} \cdot \frac{\partial i_{pv}}{\partial v_{pv}}
\]

(3)

The (3) concludes that after reiterated adjustment, a referral voltage value \( x_1^f \) received from MKGA is near the maximum power point voltage \( v_{pv}^{max} \) stably, thus getting in the maximum output. Figure 2 illustrates a SiC-based SEPIC DC-DC converter, which is adopted to regulate the maximum power point voltage. Here, the purpose of the capacitor \( C_{in} \) is to enhance response, \( R_{L1} \) stands for the equivalency inner resistance of the \( L_1 \), \( R_{L2} \) denotes for the equivalency inner resistance of the \( L_2 \), \( v_{dc} \) means DC output voltage, and \( i_o \) indicates output current. In order to obtain the reinforced
The efficacy of PV power generation systems, the capability of the MPPT must be requested. Particularly, it should be beware that once the PV array is partially shaded, the feature of power-voltage curve will be multi-peaked form as shown in the Figure 3. While habitual maximum power point tracking methodologies (e.g. intervention observation, incremental conductivity, hill climbing, etc.) are used, the system state will fall into local maximum power points rather than global extreme. Other algorithms such as greedy algorithm and ant colony optimization algorithm show that the greedy algorithm offers a high-speed solution, but it confines itself to a local searching rather than a global searching, thus suffering from the weakness of a tendency to converge to a local solution; in contrast, the ant colony optimization algorithm displays improved capability in seeking the best solution, but it has the drawback of needing a more extended period of search and easily stopping at a certain solution.

\[ \begin{align*}
    & x_1 = v_{pv} \\
    & x_2 = i_{L1}
\end{align*} \]

From Figure 1 and making \( x_1 = v_{pv} \) and \( x_2 = i_{L1} \), the state space equation can be written as

\[ \begin{align*}
    \dot{x}_1 &= (i_{pv} - x_2)/C_{in} \\
    \dot{x}_2 &= [(x_1 - R_{L1} x_2 - v_{c1} - v_{c2}) + (v_{c1} + v_{c2}) \cdot u)/L_4
\end{align*} \] (4)

where \( u \) stands for control input.

The referral voltage value \( x_1^r \) is tracked by the \( x_1 \) that implies the control intension. But, the output behavior may be influenced by the outer load interventions, the changes of daylight and temperature, and the converter’s nonlinear parameters. As these uncertainties are pondered, a monkey-king genetic algorithm-based enhanced terminal attractor is applied to PV power generation system so that the faster response and more robust output can be generated. The control block diagram of the completed system displayed in Fig. 4 reveals that the state error can be converged to the origin once the presented control law \( u \) is adequately designed.

Allow the tracking error and its derivative be \( \tilde{x}_1 \) and \( \tilde{x}_2 \), respectively, and using the (5), the error state-space equation can be expressed as

\[ \begin{align*}
    \dot{\tilde{x}}_1 &= \tilde{x}_2 - \tilde{x}_1^r \\
    \dot{\tilde{x}}_2 &= [(i_{pv} - G(x) - H(x) \cdot u)]/C_{in} - \tilde{x}_1^r + \phi
\end{align*} \] (5)

where \( G(x) = (x_1 - R_{L1} x_2 - v_{c1} - v_{c2})/L_4 \), \( H(x) = (v_{c1} + v_{c2})/L_4 \), and \( \phi \) symbolizes the changes of daylight and temperature, and outer loading interventions.

Create a sliding-manifold function as

\[ S = \tilde{x}_1 + e^{-1}\tilde{x}_1^r \] (6)
where \( \varepsilon > 0 \), and \( \ell \) is bounded by \( 0.5 < \ell/2 < 1 \). The enhanced terminal attractor involving a power reaching law can be chosen as

\[
\dot{S} = [-\delta_1 S_1^k \tanh() - \delta_2 |S|^k \tanh() \cdot (1 + \gamma \|\vec{z}_{\infty}\|_\infty)]
\]

where \( \delta_1 > 0, \delta_2 > 0, k_1 > 1, 0 < k_2/2 < 0.5, \gamma \) is a changeable parameter, and \( \|\vec{z}_{\infty}\|_\infty \) means the infinite norm of state variables.

By the use of the (5)-(7), the presented control law yields

\[
u(t) = -[G(x) - i_{pv} + C_{in} \vec{i}_4 + e^{-1}\vec{z}_{\infty}^{2-\ell} + [\delta_1 |S_1|^k \tanh() + \delta_2 |S|^k \tanh()] \cdot (1 + \gamma \|\vec{z}_{\infty}\|_\infty)] / \bar{H}(x)
\]

Then the monkey-king genetic algorithm is utilized to find the global MPPT, and the detailed operation steps are as follows:

Step 1: Defining the ratio of monkey king particles involved in current populations.
Step 2: Defining the amount of small monkeys that divides from a monkey king for the development.
Step 3: The development is written as

\[
Z_{lm} = \{z_1, z_2, ..., z_g, ..., z_{Q}\}
\]

\[
z_g \rightarrow z_g = \frac{1}{5} * \text{ram}(x) * z_g \quad \text{where} \quad g \in W
\]

where \( W \) stands for constant value and dimension, \( Z_{lm} \) indicates the population of small monkeys presented in count \( V \times W \), and \( g \) denotes a small monkey particle in \( Z_{lm} \).

Step 4: The subsequent generation of particles can be gained from the currently available generation of baby monkeys as follows:

\[
X_{\text{MKEA}}^{n+1} = \text{Opt}(V \times X_{\text{MKEA}}(1), ..., V \times X_{\text{MKEA}}(k), ..., V \times X_{\text{MKEA}}(V \times W)) \quad \text{where} \quad k \in V \times W
\]

where \( V \) signifies constant value and dimension.

Step 5: The searching procedure for other particles would be

\[
Z_{j}^{n+1} = Z_{j}^{p\text{best}} + U * \text{ram}(x) * (Z_{j}^{\text{gbest}} - Z_{j}^{p\text{best}})
\]

where \( j \) indicates the particle, \( n \) is the number of iterations, \( p\text{best} \) denotes the preceding best of the \( j \) th particle, and \( g\text{best} \) implies the particle with the global best solution discovered to date, starting with iteration one.

3. Results and discussions

The PV electrical specifications are provided in Table 1 and the system parameters are given in the following: The SEPIC converter has an inductance of 53 mH, an inner resistance of 131 m\( \Omega \), an input capacitance of 330 \( \mu \)F and an output capacitance of 2700 \( \mu \)F. The full-bridge inverter owns an inductance of 0.5 mH, a capacitance of 10 \( \mu \)F, a DC link voltage of 205 V, a rated load of 12 ohm, a requested referral voltage (110 Vrms, 60 Hz), and a switching frequency 15kHz.

| Table 1. PV electrical specifications. |
|---------------------------------------|
| (Irradiance 1 kW/m\(^2\) and Module temperature 25°C) |
| Rated Power | 75 W |
| Rated Working Voltage | 17 V |
| Rated Working Current | 4.4 A |
| Open-Circuit Voltage | 21.7 V |
| Short-Circuit Current | 4.8 A |
| Ideality Factor of the Diode | 1.2 |
| Temperature Coefficient of Short-Circuit Current | 4 mA/°C |
| P-N junction parameter | 2.035 |
Figure 5 reveals the simulated stationary behaviour of the final output-voltage $v_{ac}$ for the proposed control technology under rectifying load conditions. It can be viewed from the Figure 5 that the proposed control technology is impervious and robust to non-linear loading. Figure 6 provides a simulated waveform of the final output-voltage $v_{ac}$ for the conventional TA subject to a rectifier load, which is vulnerable to non-linear loads and the waveform is markedly warped. Thus, Figure 5 illustrates that the proposed control technology can perform high-level performance in terms of final full-bridge stabilisation response, verifying the usefulness of the MKGA algorithm.

Figure 5. Proposed control technology under rectifier load (vert.: 50 V/div).

Figure 6. Conventional TA under rectifier load (vert.: 50 V/div).

Figure 7 displays the experimental output-voltage $v_{ac}$ of the proposed control technology from unloaded to fully loaded at an ignition angle of 90 degrees. As can be appreciated, the proposed control technology has a mild temporary voltage dropping and a quick steady state restoration. Figure 8 is the experimental output-voltage $v_{ac}$ of the change of abrupt load from unloaded to fully loaded at 90 angles for the conventional TA. The output response offers unfavorable dynamic behaviour with larger output-voltage dropping and slower recuperation.

Figure 7. Proposed control technology under abrupt load change.

Figure 8. Conventional TA under abrupt load change.

4. Conclusions
In this paper, a photovoltaic power generation system integrating enhanced TA together with monkey-king genetic algorithm has successfully obtained low-aliasing output-voltage in the presence of non-linear loading and abrupt load change. Conventional TA can quickly reach the state equilibrium point in a limited time, however once it encounters a highly non-linear loading, the speed and stability of the system-state convergence will be greatly reduced. Compared with the conventional TA, the enhanced TA achieves faster convergence and ensures stability under various loading scenarios, and then monkey-king genetic algorithm helps to find global optimization parameters when the PV array is
subjected to uncertainties. The results of simulations and experiments have confirmed the suitability as well as the availability of the proposed control technology.

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