A maximum power point prediction method for group control of photovoltaic water pumping systems based on parameter identification

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Abstract. This paper puts forward a maximum power estimation method based on the photovoltaic array (PVA) model to solve the optimization problems about group control of the PV water pumping systems (PVWPS) at the maximum power point (MPP). This method uses the improved genetic algorithm (GA) for model parameters estimation and identification in view of multi P-V characteristic curves of a PVA model, and then corrects the identification results through least square method. On this basis, the irradiation level and operating temperature under any condition are able to estimate so an accurate PVA model is established and the MPP none-disturbance estimation is achieved. The simulation adopts the proposed GA to determine parameters, and the results verify the accuracy and practicability of the methods.

1. Introduction

PV pump, directly driven by solar energy has many advantages such as environmentally friendly, low maintenance cost and simple operation [1-3]. In group control of PVWPS, the output power amplitude of the PVA is scheduled according to the P-V curve. In the process of the group system operation, if the pump output frequency has not reached the maximum limit yet, the output power of the converter is MPP of the PVA. However, if the irradiation gradually increasing, the pump output frequency achieves the maximum limit, thus the array operating voltage deviates from the maximum power point voltage. Under this circumstance, the actual maximum power is not able to be measured directly.

To solve this contradiction, in recent years, domestic and foreign scholars have proposed MPP estimation method based on PVA mathematical model. The main idea is to identify the uncertain parameters of a PVA and get the complete P-V characteristic curve on the basis of mathematical model. Literatures [4-5] present a five parameter mathematical model based on the equivalent circuit model which take the influences of parallel resistance and the photogenic current into account. This method has a relatively high precision, but quite complicated that is not suitable for engineering calculation. Literatures [6-7] simplified the model under the premise of ensuring the accuracy but it is also needed to determine the slope value of the open circuit voltage. Besides, literature [8-9] neglect the series resistance and the shunt resistance in the model and provide a conversation relationship between the different solar irradiation level and operating temperature which have a lot of practical engineering values.
In this paper, a new MPP estimation method is proposed, in which influencing parameter, solar irradiation level and operating temperature are regarded as unknown parameters. The improved GA is used to identify and predict PV curves, and the least squares method is used to correct multiple sets of parameters. On this basis, solar irradiation level and operating temperature under any working condition are predicted, and the P-V curve is obtained, and finally the estimation of MPP is realized. In this paper, the accuracy and practicability of the proposed method are verified by comparing the power predicted value and the measured value under three kinds of operating conditions.

2. Group control of PVWPS

During the operation of group control of PVWPS, when the pump speed does not reach the saturation speed and the system has been in MPPT state, the PVA will operate at its MPP (A) as shown in Figure 1 As shown in curve 1. When the array power increases, the array operating point will deviate from point A', and the pump speed does not reach the critical saturation state, thus the system runs in MPPT mode. At this point the array still works at its MPP (B), the array of working conditions as shown in curve 2, when the pump has reached its upper speed limit; As the illumination continues to increase and the array power continues to rise to curve 3, the array operating point will deviate from point B', and MPP can’t be further tracked due to the upper pump speed. Since the array operating voltage point deviates from MPP, MPP of the array can’t be sampled directly, so MPP in curve 3 need to be estimated.

3. PV modeling

In practical application, considering the internal defects of semiconductor crystal and effect of series and parallel, we can think the contact resistance and material body resistance are equivalent to the internal series resistance and the effect of the leakage current in the component is equivalent to a parallel resistance in the PV equivalent circuit shown in the Figure 2.

![Figure 2. Simplified-equivalent circuit of PV cell.](image)

The current equation of PV module DC model [10] expressed as Equation (1):

\[ I = I_{ph} - I_0 \left( \exp \left[ \frac{q}{nKT_c} (U + IR) \right] - 1 \right) - \frac{U + IR}{R_{sh}} \]  

(1)
where \( I \) is cell output current, \( A \); \( I_{ph} \) is photocurrent, function of irradiation level and junction temperature, \( \alpha \); \( I_0 \) is reverse saturation current of diode, \( A \); \( q \) is electron charge \((1.6 \times 10^{-19} \text{C})\); \( K \) is Boltzmann constant \((1.38 \times 10^{-23} \text{J/K})\); \( T_c \) is reference cell operating temperature, \( K \); \( n \) is diode factor; \( R_s \) is series resistance of cell, \( \gamma \); \( R_{sh} \) is shunt resistance of cell, \( \gamma \); \( U \) is cell output voltage. Under the standard test conditions, the equivalent circuit model parameters are denoted by the subscript ref, which is different from other operating conditions.

In ensuring a certain accuracy, solar cell model for engineering uses the following two approximations.

1) \((U+IR_s)/R_{sh}\) is very small and the effect on the battery current is very small, which can be ignored.

2) \(R_s \) is much less than the diode forward resistance, we can consider that \( I_{ph} = I_{sc} \).

Under the assumption above to further reduce the parameters of I-V equation, we can use as Equation (2) to fit the I-V characteristic curve of silicon solar cells:

\[
I = I_{sc} \left[ 1 - C_1 \left( \exp \left( \frac{U}{C_2} \right) - 1 \right) \right]
\]

We can derive as Equation (3) with the equations: \( U = U_m \) and \( I = I_m \) when reaching the maximum power point, \( I = 0, U = U_{oc} \) when in open state.

\[
\begin{align*}
I_m &= I_{sc} \left[ 1 - C_1 \left( \exp \left( \frac{U_m}{C_2} \right) - 1 \right) \right] \\
0 &= I_{sc} \left[ 1 - C_1 \left( \exp \left( \frac{U_{oc}}{C_2} \right) - 1 \right) \right]
\end{align*}
\]

(3)

On the condition of room temperature, we can think \( \exp(U/C_2) >> 1 \) and simplify the Equation (3) to Equation (4):

\[
\begin{align*}
C_1 &= \left( 1 - \frac{I_m}{I_{sc}} \right) \exp \left( - \frac{U_m}{C_2} \right) \\
C_2 &= (U_{oc} - U_m) \left[ \ln \frac{I_{sc}}{(I_{sc} - I_m)} \right]^{-1}
\end{align*}
\]

(4)

Thus, we can obtain a two-parameter model of PV consisting of only 2 unknown parameters \( C_1 \) and \( C_2 \). According to the Equation (3), we can get the value of the unknown parameters of \( C_1 \) and \( C_2 \) when the parameters of the solar cell in different operating conditions the short-circuit current \( I_{sc} \), the open-circuit voltage \( V_{oc} \), the maximum power point current \( I_m \), the maximum power point voltage \( V_m \) are obtained. As the characteristics of photovoltaic cells is relevant to the solar irradiation level \( S \) and operating temperature \( T_c \), voltage and current will change with \( T_c \) and \( S \) changes, and thus \( C_1 \) and \( C_2 \) will change together. When the ambient temperature \( T_a \) and \( S \) change, \( T_c \) also change. The influence factor of \( T_a \) changes on the output voltage and current of the PV array is expressed by \( C_{TV} \) and \( C_{TI} \), as Equation (5) respectively. The change of \( S \) will promote the photovoltaic current and operating temperature changes resulting in changes in output voltage. The influence factor of irradiation levels changes on the output voltage and current can be expressed by \( C_{SV} \) and \( C_{SI} \) [11]:

\[
\begin{align*}
C_{TV} &= 1 + \frac{\beta (T_a - T_{ref})}{T_{ref}} \\
C_{TI} &= 1 + \frac{\lambda (T_a - T_{ref})}{S_{ref}} \\
C_{SV} &= 1 + \alpha (S - S_{ref}) \\
C_{SI} &= 1 + \frac{(S - S_{ref})}{S_{ref}} = \frac{S}{S_{ref}}
\end{align*}
\]

(5)

where \( \alpha \) means the influence of solar irradiation level of the change on the output voltage the photovoltaic cell, \( \beta, \lambda \) mean the influence of the ambient temperature on the output voltage and current of the photovoltaic cell. \( T_{ref} \) and \( S_{ref} \) are the ambient temperature and the irradiation level under standard test conditions (STC). Considering the effect of \( T_a \) and \( S \) change on the output voltage and current, the current output voltage and current can be obtained by using the correction factors \( C_{TV}, C_{TI}, C_{SV} \) and \( C_{SI} \) at the new \( T_a \) and \( S \) as Equation (6):

\[
\begin{align*}
U' &= U_{ref} C_{TV} C_{SV} \\
I' &= I_{ref} C_{TI} C_{SI}
\end{align*}
\]

(6)
Because the $\alpha, \beta, \lambda$ parameters is related to battery performance, and can be effected by the photovoltaic cell technology or series and parallel, the experience factor is not precise enough. At the same time, the current $T_a$ and $S$ of photovoltaic cells can’t be accurately obtained in the project.

4. Application of GA in group control of PVWPS

4.1. Genetic algorithm

Genetic algorithm is an efficient parallel global search algorithm based on the natural selection and genetic principle [12]. In this paper, we propose an improved GA, that is, the optimal individual preservation method, which preserves the optimal individuals of the parent each time, which improves the convergence and does not lose the overall situation. The steps includes initialization control parameters, population initialization, fitness evaluation, selection operation, cross operation, termination condition judgment and so on. The novel genetic algorithm flow chart is shown in Figure 3:

![Flowchart of improved GA](image)

**Figure 3.** The flowchart of improved GA.

4.2. Application of genetic algorithm in parameter recognition

Objective function: The problem of parameter identification of photovoltaic array model is transformed into the minimum value of objective function as Equation (7):

$$min C = \sum_{j=1}^{k} (P_j^* - P_j)^2 + \Delta C$$

$P_j^*$ is the predicted power, $I_{sref}$, $U_{ocref}$, $I_{mref}$ and $U_{mref}$ of a PV module under STC provided by manufacturers with identify parameter values, combining the Equation (1), Equation (3) and Equation (5); $P_j$ is the measurement power of the photovoltaic array; $k$ is the number of measured data; $\Delta C$ is the penalty function that does not satisfy the constraint condition.

Constraint condition: As Equation (8)

$$\begin{align*}
|U_m' - U_m| &\leq \delta_1 \\
|I_m' - I_m| &\leq \delta_2 \\
|P_m' - P_m| &\leq \delta_3
\end{align*}$$
\(U_m, I_m, P_m\) are the actual maximum power voltage, current, power collected by photovoltaic water pump MPPT under different operating conditions. \(U_m^*, I_m^*, P_m^*\) are maximum power point of photovoltaic array model based on GA parameter identification under different operating conditions. \(\delta_1, \delta_2, \delta_3\) are the identification range and the actual error range.

Parameter identification process shown in Figure 4, according to different conditions under MPP of the PV pump to capture the collected data, The k group data are extracted separately from the curves 1 and 2 in Figure 1. Using the improved GA for parameter identification and estimation, \(\alpha_i, \beta_i, \lambda_i, T_i\) and \(S_i\) under different conditions were obtained, and the least squares method was used to modify \(\alpha, \beta\) and \(\lambda\). Using the data collected by curve 3 and combining \(\alpha, \beta, \lambda\) to predict \(T\) and \(S\), we can obtain the \(P-V\) curve 3 under the current condition. However, it is found that the \(\alpha, \beta\) and \(\lambda\) is not high enough. Thus, in response to this problem, this paper uses a step-by-step method to improve the accuracy of parameter identification parameters. GA is used to estimate \(S\) under different conditions. Then, the estimated parameters of \(S\) are taken as the known parameters and then identification of \(\alpha_i, \beta_i, \lambda_i\) and \(T_i\) are carried out according to the improved GA. The multi-group identification parameters are modified by the least squares method. Finally, using the modified parameters and the measured data to estimate the current \(T_a\) and \(S\), combined with PV model to predict the current MPP of the PVA.

### 5. Simulation experiment and result analysis

According to the empirical data, the range of PV model parameters: 0.0008 \(\leq \alpha \leq 0.001\); 0.0035 \(\leq \beta \leq 0.0045\); 0.05 \(\leq \lambda \leq 0.07\); 0 \(\leq S \leq 2000\); 0 \(\leq T \leq 40\). In genetic algorithm, the relevant parameter values are set as shown in Table 1. In the table, \(N\) is the population size; \(Gen_{max}\) is the maximum evolutionary algebra; \(P_c\) is the crossover probability; \(P_m\) is the mutation probability.

| Parameters | Traditional program | Improve program |
|------------|--------------------|----------------|
| \(N\)      | 200                | 200            |
| \(Gen_{max}\) | 100                | 500            |
| \(P_c\)    | 0.85               | 0.85           |
| \(P_m\)    | 0.08               | 0.08           |
Track the collected data when the PV pump is at the maximum power point, then run the genetic algorithm to get the convergence curve as shown in Figure 5:

![Convergence Curves](image)

(a). Traditional method.  
(b). Improved method.

Figure 5. The relationship between objective function and evolution generations of genetic algorithm.

It can be seen from Figure 5 in the graph (b) the objective function is smaller than the graph (a), and parameter identification result is more accurate.

In this paper, we use four groups of photovoltaic in the state of water MPP to capture the collected data, and identify the model parameters. The PV cell parameters are identified in Table 2.

| Parameters | Curve 1 | Curve 2 | Curve 3 | Curve 4 | Correction parameters |
|------------|---------|---------|---------|---------|-----------------------|
| $\alpha/10^{-3}$ | 0.8007 | 0.8010 | 0.8001 | 0.8039 | 0.8012 |
| $\beta$ | 0.0039 | 0.0041 | 0.0041 | 0.0040 | 0.0040 |
| $\lambda$ | 0.0602 | 0.0605 | 0.0602 | 0.0601 | 0.0602 |
| $T_a$ | 20.0117 | 22.1575 | 24.9999 | 25.8682 | \ |
| $S$ | 599.5 | 799.6 | 1000 | 1199.9 | \ |

Based on $\alpha$, $\beta$ and $\lambda$ three sets of measured data were used to estimate the current $T_a$ and $S$ by GA. Figure 6 shows the comparison chart of the model simulation results and the measured value, we can see that the model based on the identification of the model output is better matched to the measured value and meet the requirements of photovoltaic modules engineering modelling better.

According to the above analysis, it can be used to accurately estimate the operating temperature and irradiation level based on the parameter values identified by the PVA parameter identification method, and then we can draw out a much more accurate P-V curve to estimate MPP which proves the validity and practical value of the method.

![Simulation vs Measured Values](image)

Figure 6. Comparison of simulation results with measured values.

6. Summary
In this paper, a new method combined with parameter identification of PVA, prediction of temperature and irradiation level, is proposed. Using the PVA measured data, GA can be used to identify
parameters and predict $T_a$ and $S$. The identification accuracy of parameter identification is not enough, and improve the accuracy of parameter identification by improved method. The actual example shows that the parameter value based on the method proposed in this paper is more accurate, and then an accurate PVA model can be established to predict the MPP of the PVA.

References
[1] Su Jianhui 2003 A Research on Photovoltaic Water Pumping System and its Control Strategy Hefei University of Technology
[2] Xu Zheng, Zeng Pijiang, Zhang Fei and He Shaoqiang 2015 Research and Development of PV Reverse Osmosis Desalination Systems Acta Energiae Solaris Sinica 36(4) pp 886-92
[3] Liu Peng, Su Jianhui and Wu Wenjin 2016 Research on Control Strategy and Stability of Common DC Bus Solar Pumper Cluster System Power Electronics 50(10) pp 67-9
[4] Kennerud K L 1969 Analysis of Performance Degradation in CdS Solar Cells Aerospace and Electronic Systems 5(9) pp 912-7
[5] Jian Xianzhong, Wei Kai and Guo Qiang 2015 Artificial Bee Swarm Algorithm in the Application of Photovoltaic Cell Five-parameter Double-diode Model Acta Photonica Sinica 44(1) pp 168-72
[6] Chan D S H, Phillips J R and Phang J C H 1986 Acomparative Study of Extraction Methods for Solar Cell Model Parameters Solid-State Electronics 29(3) pp 329-37
[7] Xu Xiaobing, Wang Jianping and Zhang Chongwei 2009 Analytical Model and Parameter Revising Method of Silicon Solar Cells Journal of Hefei University Of Technology 32(2) pp 166-9
[8] Su Jianhui, Yu Shijie and Zhao Wei 2001 Investigation on Engineering Analytical Model of Silicon Solar Cells Acta Energiae Solaris Sinica 22(4) pp 409-12
[9] Qiu Chun, Cai Tao, Duan Shanxu, Dai Qian, Shen Yanbo and Chen Zhenghong 2013 Extraction of Solar Cell Model Parameters under Arbitrary Irradiance and Cell Temperature Acta Energiea Ssolaris Sinica 34(9) pp 1626-32
[10] Rauschenbach H S 1980 Solar cell and its application (USA: Litton Educational Publishing Inc)
[11] Altas I H, Sharaf A M 2007 A Photovoltaic Array Simulation Model for Matlab-Simulink GUI Environment International Conference on Clean Electrical Power IEEE pp 341-5
[12] Cao Daoyou 2010 Research and Applications Based on Improved Genetic Algorithm Anhui University