Establishment and Optimization of Mathematical Model for Total Equivalent Power of PV/T System

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Keywords: PV/T, total equivalent power, quantum genetic algorithm, parameter optimization.

Abstract: The establishment and optimization of the total equivalent power objective function of PV/T system plays a vital role in the optimal control of the system. Based on the flat water-cooled solar photovoltaic and photothermal comprehensive utilization system, this paper studies and establishes the total equivalent power mathematical model of PV/T system per unit time. Secondly, in order to improve the optimization effect of output total equivalent power objective function parameters, quantum genetic algorithm is applied to the optimization of system output total equivalent power objective function parameters. Finally, the comparison of simulation experiments shows that, Using quantum genetic algorithm for parameter optimization has the advantages of fast convergence speed, avoiding falling into local optimization and faster convergence to global optimization.

1. Introduction

In order to make full use of solar energy resources and improve the energy utilization efficiency of PV/T system, it is necessary to track the maximum power point on the basis of establishing an accurate total equivalent power model of the system. Although PV/T comprehensive utilization system is currently a hot research topic, there is little research on the total equivalent power model of PV/T comprehensive utilization system. However, the research on the total equivalent power model of flat water-cooled PV/T comprehensive utilization system plays a vital role in the subsequent optimal control. On the other hand, it can also make up for the lack of the basic theoretical basis for the establishment of the total equivalent power model of the flat water-cooled PV/T comprehensive utilization system. Therefore, it is of great significance to study the total equivalent power model of flat water-cooled PV/T comprehensive utilization system.

At present, a large number of researches have been made on PV/T system at home and abroad, mainly focusing on how to reduce the PV/T module temperature, PV/T module temperature prediction and photovoltaic cell output characteristic modeling. Literature [1, 2] analyzes the influencing factors of PV/T module temperature, and puts forward short-term prediction methods of PV/T module temperature based on RBF neural network and PCA-Elman neural network respectively according to temperature curves of different weather. Literature [3] conducted simulation research on the dynamic characteristics and application of PV/T system. Photoelectric system analyzed the equivalent circuit of photovoltaic cell and established mathematical simulation model.Literature [4] studies the modeling of photovoltaic system output characteristics under arbitrary irradiance and temperature conditions. Literature [5] studies the influence of flow change on PV/T system performance, which provides a theoretical basis for optimizing system performance under variable flow operation. The optimal control of flat water-cooled PV/T integrated utilization system depends not only on component temperature prediction but also on the establishment of the total equivalent power model of the system output. However, the electrical power modeling of photovoltaic cell output is only a part of the total equivalent power modeling of flat-panel water-cooled PV/T comprehensive utilization system, and the research on the total equivalent power modeling of system output from the overall perspective of PV/T system is deficient.

Firstly, based on the analysis of flat-plate water-cooled PV/T system and the existing photovoltaic cell output characteristic model, this paper also studies the thermal energy model of solar collector and the energy consumption model of water pump. According to the relationship between system capacity and energy consumption, the total equivalent output power model of flat water-cooled PV/T comprehensive utilization system is obtained. Finally, based on the successful modeling of the total equivalent power output of the system, The quantum genetic algorithm is used to optimize the parameters of the total equivalent power function of the system output. In order to verify the superiority of quantum genetic algorithm, the optimization results of objective function parameters of total equivalent power output by genetic algorithm are compared. The comparison results show that quantum genetic algorithm parameter optimization algorithm is superior to genetic algorithm.

2. Introduction of PV/T Experimental Platform

In this paper, the water-cooled PV/T system is studied, as shown in Figure 1 [6]. The water pump in the water tank is controlled by the controller to cool the water pump to the PV/T component and continuously circulate. The temperature of the PV/T component is reduced while the heat is accumulated, so as to improve its power generation efficiency and realize the comprehensive utilization of heat energy and electric energy.

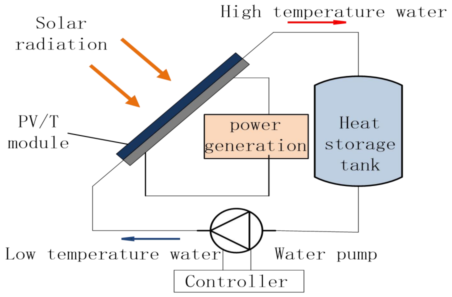

Figure 1: Schematic diagram of PV/T system.

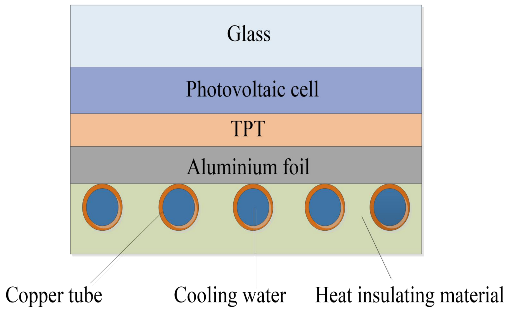

Figure 2: Structure of PV/T module.

Figure 2 [7] is the PV/T module longitudinal structure diagram. From top to bottom, it is glass cover layer, photovoltaic cell layer, solar cell back film (TPT) layer, aluminum foil layer and copper tube layer.

3. Establishment of Mathematical Model of Photovoltaic Photothermal Total Equivalent Power

3.1. Power Generation of Photovoltaic Cells Per Unit Time

As the voltage and current of photovoltaic power generation will change with the change of the external environment, The main influencing factors are irradiation intensity and photovoltaic cell temperature [8]. Therefore, under the condition that the external load is determined, the output expressions of photovoltaic cells under different light intensities and temperatures are obtained. By referring to a large number of literatures, the output characteristic expression of voltage and current under different illumination intensity and battery temperature is obtained as follows [4-5]:

$$\Delta T = T_{pv} - T_{ref} \tag{1}$$

$$\Delta S = S - S_{ref} \tag{2}$$

$$I_{oc}^{'} = I_{oc} \cdot \frac{S}{S_{ref}}(1 + a\Delta T) \tag{3}$$

$$V_{oc}^{'} = V_{oc} \cdot \ln(e + b\Delta S)(1 - c\Delta T) \tag{4}$$

$$I_{m}^{'} = I_{m} \cdot \frac{S}{S_{ref}}(1 + a\Delta T) \tag{5}$$

$$V_{m}^{'} = V_{m} \cdot \ln(e + b\Delta S)(1 - c\Delta T) \tag{6}$$

In the formula, I_{oc}, V_{oc}, I_m, V_m Under standard conditions respectively（$T_{ref} = 25℃, S_{ref} = 1000W/m^2$）Circuit current, open circuit voltage, maximum power point current and voltage,These values are provided by manufacturers according to the type and material of photovoltaic cells. $I_{oc}^{'}$, $V_{oc}^{'}$, $I_m^{'}$, $V_m^{'}$ Is the $I-V$ characteristic curve under any illumination intensity s and any photovoltaic cell temperature T_{pv}.

$I_m^{'}$ and $V_m^{'}$ at any known light intensity and photovoltaic cell temperature, According to the formula, the output power of the photovoltaic cell is obtained:

$$P_v(T_{pv}, S) = I_m^{'} \times V_m^{'} = I_m \frac{S}{S_{ref}}(1 + a\Delta T) \times V_m \ln(e + b\Delta S)(1 - c\Delta T) \tag{7}$$

Substituting Eq. (5) and (6) into Eq.(7), the output power mathematical formulas for photovoltaic cell temperature T_{pv} and irradiation intensity S can be obtained:

$$P_v(T_{pv}, S) = I_m \frac{S}{S_{ref}}[1 + a(T_{pv} - T_{ref})] \times V_m \ln[e + b(S - S_{ref})][1 - c(T_{pv} - T_{ref})] \tag{8}$$

In formula (8), T_{ref} and S_{ref} are the reference temperature and reference irradiation intensity under standard conditions; I_m and V_m are the maximum power point current and voltage under standard conditions respectively. According to the models of photovoltaic cells in this topic, the values provided by the manufacturers are $I_m = 2.86A$, $V_m = 35V$;a, b and c are compensation coefficients obtained by curve fitting based on a large amount of experimental data a=0.0025(℃)$^{-1}$, b=0.0005$(W/m^2)^{-1}$, c=0.00288(℃)$^{-1}$. Substituting the above known values into Eq. (7) can obtain the mathematical model of photovoltaic cell electric power per unit time:

$$\begin{aligned}P_v(T_{pv},S) &= I_m\frac{S}{S_{ref}}[1+a\left(T_{pv}-T_{ref}\right)]\times V_m\ln(e+b\Delta S)[1-c(T_{pv}-T_{ref})] \\ &= 2.86\frac{S}{1000}[1+0.0025\left(T_{pv}-25\right)]\times 35\ln[2.718+0.005(S-1000)][1-0.00288(T_{pv}-25)]\end{aligned} \tag{9}$$

3.2. Heat Power Collected by the Heat Collecting Tank Per Unit Time

The actual heat collected by the PV/T collector per unit time can be calculated by the heat taken away by the cooling water per unit time. If the mass of water flowing through the heat collector per unit time is $M(kg)$, passing through the heat collector, the temperature rises ΔT_w, If the heat absorbed by the water flow after passing through the heat collector per unit time is Q_m, it can be regarded as the heat collector doing work on the water, and the calculation formula of the heat absorbed is as follows:

$$Q_m = C_w M\Delta T_w = \mathrm{C}_w M(T_{out}-T_{in}) \tag{10}$$

In the above formula, C_w is the specific heat capacity of water, T_{in} and T_{out} are the water temperatures at the inlet and outlet of the heat collector respectively.

In this paper, the flow volume of cooling water measured by the flow sensor is $V(L/\min)$, then the flow volume flowing through the heat collector per unit time is $V\times10^{-3}/60(m^3/s)$, the density of cooling water is $\rho = 1\times10^3 kg/m^3$, and the mass flowing through the heat collector per unit time is $M(kg)$, which is:

$$M = \rho\times V\times10^{-3}/60 = 1\times10^3\times V\times10^{-3}/60 = V/60 \tag{11}$$

Substituting Eq. (11) into Eq. (10) above, the heat collected from PV/T collector by the unit time heat collecting tank is as follows:

$$Q_m = C_w M\Delta T_w = \mathrm{C}_w V(T_{out}-T_{in})/60 \tag{12}$$

Eq. (12) gives the mathematical formula of the heat model of the heat collecting tank. The specific heat capacity of cooling water $\boldsymbol{C_w} = 4.2\times10^3\boldsymbol{J}/(\boldsymbol{kg}\bullet℃)$ is a known value. V is the flow volume flowing through the heat collector in a unit time and cannot be directly obtained. T_{in} and T_{out} are the inlet and outlet water temperatures of the heat collector respectively, which can be measured by temperature sensors in the inlet and outlet pipelines.

As for the specific relation between the cooling water flow volume V and the pump frequency f cannot be directly obtained, this paper makes regression analysis based on the data collected when starting the pump operation system, collecting cooling water flow values under different water pump frequencies through a flow sensor. Using the "least square method" to fit the data curve, the relationship between cooling water flow and pump frequency in unit time is obtained:

$$V = 0.1840f - 1.8736 \tag{13}$$

The formula (13) obtained after regression analysis and the specific heat capacity value $\boldsymbol{C}_w = 4.2\times10^3 \boldsymbol{J}/(\boldsymbol{kg}\bullet℃)$ of cooling water are substituted into the above formula (12) to obtain the thermal power mathematical formula obtained by the unit time heat collecting tank as follows:

$$\begin{aligned} Q_m &= C_w M \Delta T_w = \mathrm{C}_w * V * (T_{out} - T_{in})/60 \\ &= 4.2\times10^3 \times (0.1840f - 1.8736)\times(T_{out} - T_{in})/60 \end{aligned} \tag{14}$$

3.3.Electric Power Consumed by Water Pump Per Unit Time

In the total equivalent power of PV/T comprehensive utilization system studied in this paper, water pump is the equipment that mainly consumes electric energy. Frequency conversion water pump is used in PV/T system, so the main influencing factor of energy consumption is the frequency f of water pump. The pump model is HJ125E and its power is 125W. Looking up the data, it can be seen that the electric energy consumed by the pump during operation is proportional to the cubic power of the pump frequency. Therefore, the electricity consumed by the pump per unit time is:

$$P_1 = f_1(f)\times P = \left(\frac{f}{50}\right)^3 \times 125 \tag{15}$$

3.4.Mathematical Model of Total Equivalent Power of Unit Time System

In this paper, the total equivalent power output by PV/T system is the net energy obtained by the system as a whole, which is the energy obtained by the system minus the power consumption of the system. In actual production, electric energy belongs to high-grade energy and thermal energy belongs to low-grade energy. When the two are calculated in the same formula, they need to be converted according to the power generation efficiency of conventional thermal power plants. In general, the efficiency of converting thermal energy into electrical energy in thermal power plants is $\eta_{power} = 0.38$. According to the above analysis, the total equivalent power formula of the system output per unit time is:

$$Q = \frac{P_v}{\eta_{power}} + Q_m - \frac{P_1}{\eta_{power}} \tag{16}$$

According to the previous analysis, the total equivalent power Q is a multivariate multiple nonlinear equation related to the irradiation intensity s, the photovoltaic cell temperature T_{pv}, the water pump frequency f and the inlet and outlet water temperatures T_{in} and T_{out} of the collector. However, the irradiation intensity S is an uncontrollable quantity and can be directly measured by the irradiation sensor. Formula Q is simplified to a four-element nonlinear equation about T_{pv}, f, T_{in} and T_{out}. One of the research contents of this paper is to find out the optimal water pump frequency and the optimal photovoltaic module temperature when the total equivalent power of the system is maximum in the current external environment. Therefore, it is necessary to further simplify the formula and set the T_{in} and T_{out} as known quantities. The final equation (16) can be regarded as a binary non-linear equation of the total equivalent power Q with respect to the photovoltaic cell temperature T_{pv} and the water pump frequency f, then the target function of the total equivalent power of the system is shown in the following equations:

$$\begin{cases} Q = \dfrac{P_v}{\eta_{power}} + Q_m - \dfrac{P_1}{\eta_{power}} \\ P_v = 2.86 \times \dfrac{S}{1000} \times [1 + 0.0025\left(T_{pv} - 25\right)] \times 35 \times \\ \qquad \ln[2.718 + 0.005(S - 1000)][1 - 0.00288(T_{pv} - 25)] \\ Q_m = 4.2 \times 10^3 \times V \times (T_{out} - T_{in}) / 60 \\ P_1 = \left(\dfrac{f}{50}\right)^3 \times 125 \\ V = 0.1840 f - 1.8736 \end{cases} \tag{17}$$

In the independent variables of the above formula, the irradiation intensity S, the photovoltaic cell temperature T_{pv} and the water pump frequency f are all constrained conditions. Under normal circumstances, the irradiation intensity will not exceed $1000W / m^2$; In summer, the temperature of the photovoltaic cell can reach as high as 80℃, However, in PV/T system, the temperature will not be allowed to reach 80℃, The frequency of the water pump in the PV/T system studied in this paper can be arbitrarily adjusted between 20 Hz and 60 Hz, however, considering the service life of the water pump, the power frequency of 50 Hz is taken as the upper limit. Specific constraints are shown in formula (18):

$$\begin{cases} 0 < S \le 1000 \\ 20 \le T_{pv} \le 80 \\ 20 \le f \le 50 \end{cases} \tag{18}$$

4. Analysis of Optimization Results of Total Equivalent Power Mathematical Model Based on Quantum Genetic Algorithm

4.1. Quantum Genetic Algorithm

Quantum Genetic Algorithm (QGA) is an optimization algorithm that combines quantum computation with genetic algorithm. [9, 10], Quantum state vector expression is introduced into genetic coding, and quantum bit probability amplitude is applied to chromosome coding, thus achieving better optimization effect than traditional genetic algorithm (GA),The implementation of quantum genetic algorithm will be introduced from the following aspects:

(1) Characteristics of Quantum Genetic Algorithm

Quantum genetic algorithm not only retains the advantages of genetic algorithm, but also makes up for the shortcomings of genetic algorithm, Quantum genetic algorithm has good convergence and global optimization ability, and has the following characteristics:

The population is small.

The population is diverse.

Excellent global optimization ability.

(2) Quantum bit coding

The quantum state of a qubit can be expressed by $|\varphi\rangle=[\alpha,\beta]^T$, In the binary coding of genetic algorithm, one qubit coding can be used for two-state problems and two qubit coding can be used for four-state problems.The method has strong generalization. In quantum genetic algorithm, chromosomes need to be encoded by multiple quanta, and the gene of each chromosome can be as follows:

$$\left(\begin{array}{c|c|c|c|c|c|c|c|c|c|c|c}\alpha_{11} & \alpha_{12} & \cdots & \alpha_{1k} & \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2k} & \alpha_{m1} & \alpha_{m2} & \cdots & \alpha_{mk} \\ \beta_{11} & \beta_{12} & \cdots & \beta_{1k} & \beta_{21} & \beta_{22} & \cdots & \beta_{2k} & \beta_{m1} & \beta_{m2} & \cdots & \beta_{mk}\end{array}\right) \tag{19}$$

In the above formula, m is the number of genes on the chromosome, and k is the number of qubits of the corresponding gene.

(3) Quantum revolving door

In the genetic algorithm, operations such as selection, crossover and mutation are used to update the population. However, in quantum genetic algorithm, quantum revolving door is the executive mechanism of evolutionary operation, and the population is updated by quantum revolving door. The revolving door rotates the angle according to the direction of the optimal individual of the population to achieve the purpose of updating the population, Equation (20) is its matrix formula:

$$U(\theta)=\begin{bmatrix}\cos\theta & -\sin\theta \\ \sin\theta & \cos\theta\end{bmatrix} \tag{20}$$

The update process is shown in formula (21):

$$\begin{bmatrix}\alpha_i' \\ \beta_i'\end{bmatrix}=\begin{bmatrix}\cos\theta_i & -\sin\theta_i \\ \sin\theta_i & \cos\theta_i\end{bmatrix}\begin{bmatrix}\alpha_i \\ \beta_i\end{bmatrix} \tag{21}$$

In the formula, $[\alpha_i' \quad \beta_i']^T$ is a new qubit updated by the quantum rotation gate, $[\alpha_i \quad \beta_i]^T$ is the i-th qubit of the chromosome, θ_i is the rotation angle, The rotation of the angle is determined according to a preset adjustment strategy.

(4) Quantum Genetic Algorithm Process

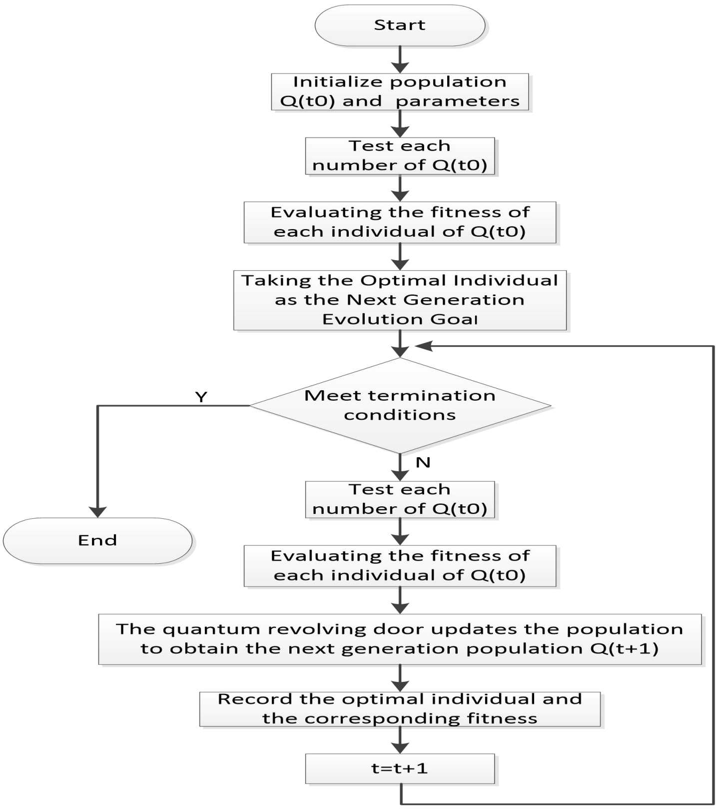

Figure 3: Quantum genetic algorithm flow chart.

4.2. Simulation Results and Analysis

In this section, genetic algorithm and quantum genetic algorithm are used to optimize and compare the objective function of PV/T total equivalent power. The parameters of genetic algorithm and quantum genetic algorithm are set as follows: The same parameters of the two algorithms are the population size popsize=20 and the maximum number of iterations generations=200;In the genetic algorithm, the mutation probability $P_M = 0.1$, the crossover probability $P_C = 0.8$, Using binary coding method; In addition to setting the algorithm parameters, the constraint conditions in the objective function variables also need to be set, the water pump frequency f is set at $20 \sim 50$ Hz, and the photovoltaic cell temperature T_{pv} is set at $20 \sim 80$℃. According to the actual situation of this experimental platform, a group of external input variables are substituted into the objective function:Light intensity $S = 799W / \mathrm{m}^2$, the inlet water temperature of the heat collector $\mathrm{T_{in}} = 32.0$°C, the outlet water temperature of the heat collector $T_{out} = 33.3$℃, maximum power point current $\mathrm{I_m} = 2.86\mathrm{A}$, maximum power point voltage $V_m = 35V$. In this external environment, the optimization results of genetic algorithm are shown in Figure 4 below, and the optimization results of quantum genetic algorithm are shown in Figure 5 below.

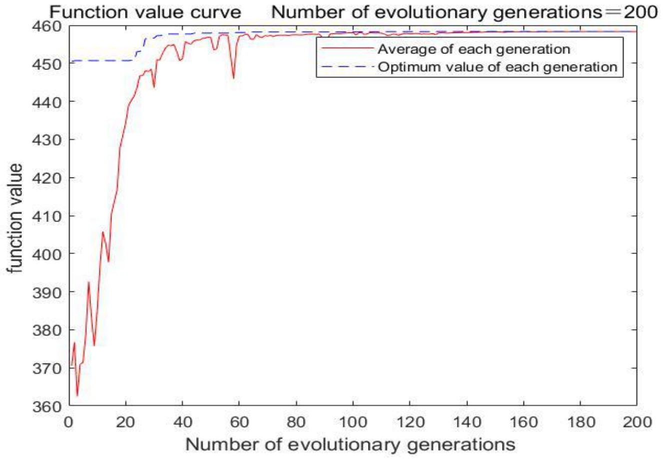

Figure 4: Optimization results of objective function based on genetic algorithm.

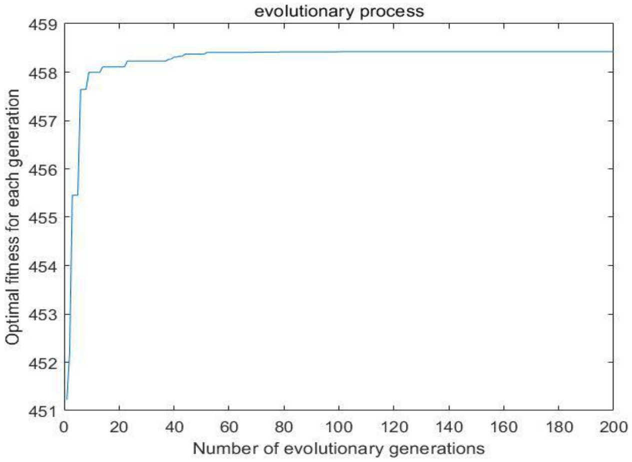

Figure 5: Optimization results of objective function based on quantum genetic algorithm.

As can be seen from Figure 4 and Figure 5, quantum genetic algorithm has faster convergence speed than genetic algorithm, can avoid falling into local optimum, and can converge to global optimum faster. Therefore, the quantum genetic algorithm is better than the genetic algorithm in optimizing the objective function of photovoltaic and photothermal total equivalent power.

5. Conclusions

Based on the flat-plate water-cooled PV/T system, this paper studies and establishes the output total equivalent power model of the flat-plate water-cooled PV/T comprehensive utilization system. The establishment of the model makes up for the deficiency of the basic theoretical basis for the establishment of the output total equivalent power model of the flat water-cooled PV/T comprehensive utilization system, and also plays a vital role in the subsequent optimization control of the system. Secondly, based on the successful modeling of the total equivalent power output of the system, the quantum genetic algorithm is applied to the objective function of the total equivalent power output of the system for parameter optimization. The comparison of simulation results shows that quantum genetic algorithm has faster convergence speed than genetic algorithm, can avoid falling into local optimum, can converge to global optimum faster, Therefore, using quantum genetic algorithm to optimize the parameters of the target function of the total equivalent power output of the system has a better optimization effect and provides a new optimization strategy for system parameter optimization.

Acknowledgments

This work was financially supported by Guangxi Natural Science Foundation Project (2014GXNSFAA118372) fund.

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