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A NEW MAXIMUM POWER POINT TRACKING ALGORITHM WITH REGIONAL LIMITED LOOP FOR THERMOELECTRIC SYSTEM

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Abstract. *In this paper, an improved variable step maximum power point tracking (MPPT) algorithm is proposed for thermoelectric generation (TEG) system. According to the characteristics of thermoelectric module (TM) revealed in this paper, the proposed algorithm will divide the power-voltage (P-V) curve into three sections. In each section, it will automatically adjust step size to promote tracking speed. In addition, a regional limited method is also proposed in this paper. Finally, the experimental system has been set up and demonstrated that the proposed MPPT algorithm brings a substantial increase for dynamic convergence process, reduces the oscillation amplitude on the maximum power point (MPP), and makes a quick adaption to the change of temperature.*
Keywords: Thermoelectric module, Maximum power point tracking, Power-voltage curve, Regional limited method

1. **Introduction.** Thermoelectric power generation is a solid green way based on the Seebeck effect of semiconductor thermoelectric chip [1]. Thermoelectric materials can scavenge the large amount of waste heat dissipated in industry applications and vehicle exhaust gas in an environmentally benign and less costly way [2].

Recently, MPPT algorithm has focused on as an important way of promoting the output power of renewable energy sources. In [3,4], advantages and disadvantages of some traditional photovoltaic MPPT algorithm are described, and the improved algorithm is proposed for better performance. In [5], the photovoltaic with MPPT is applied in grid-connected system. Due to the fact that the characteristic of P-V curve for TM is different from the conventional photovoltaic systems, there are some differences in the algorithm of MPPT. In [6], a peripheral hardware circuit is built for MPPT. It avoids the use of the algorithm to achieve the MPP, but the tracking accuracy is low, and has large oscillations at MPP. In [7], the proposed MPPT method can estimate the MPP of the TM with only current sensor by analyzing the boost chopper using state space averaging method. This algorithm has some advantages in the steady-state; however, its dynamic convergence speed is slow. In [8], the hill climb method is adopted and has a high tracking efficiency. However, it cannot make a fast tracking when the MPP changes dramatically. Aiming at the shortcomings of the existing MPPT methods, this paper presents a new algorithm for MPPT.

This paper is organized as follows. Firstly, the simulation model is built based on the physical and mathematical model of TEG. Secondly, the principle of the algorithm is analyzed, and the basic implementation process is also introduced in this paper. Finally, the experiment is conducted, and the results show that this algorithm can track the maximum power point fast and accurately.

2. TEG Characteristics.

A single TEG model is shown in Figure 1, the mathematical model can be expressed as [9]:

$$E_{TEG} = (\alpha_p - \alpha_n) \cdot (T_H - T_L) = \alpha \cdot \Delta T \tag{1}$$

where E_{TEG} is thermoelectric force, α_p is the Seebeck coefficient of p-type material, α_n is the Seebeck coefficient of n-type material, α represents the relative Seebeck coefficient of these two materials, T_H is the temperature of hot side, and T_L is the temperature of cold side.

A closed-loop circuit with load resistance is shown in Figure 2. The mathematical models of TEG system can be written as [10,11]:

$$P = U_0 \times I \quad U_0 = I \times R \tag{2}$$

$$P = \left(\frac{\alpha\Delta T}{R+r}\right)^2 \times R = \frac{\alpha\Delta T}{R+r} \times U_0 - \left(\frac{U_0}{R}\right)^2 \times r \tag{3}$$

where P is the output power of TEG, U_0 is the circuit's terminal voltage, I is the load current, R is the load resistance, and r is the internal resistance of TEG.

The characteristic curve of TEG system can be obtained by using (1)-(3). Figure 3 and Figure 4 show the P-V characteristic and P-R characteristic respectively when the temperature difference ΔT is 50°C, 100°C and 150°C respectively. The simulation results indicate that, under the maximal temperature limited by the materials, the greater the temperature difference is, the greater the output power is; when the temperature difference ΔT is unchangeable, there is an MPP on P-V curve and P-R curve. Thus, an algorithm can be established to achieve the MPP.

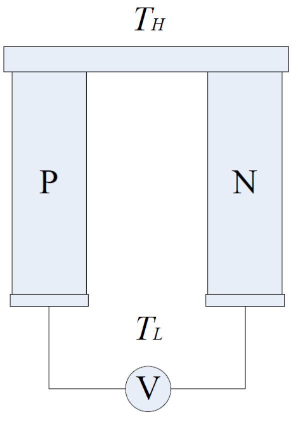

FIGURE 1. Schematic diagram of TEG model

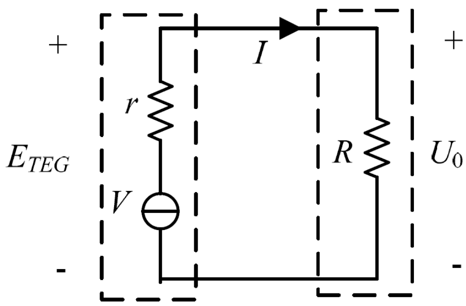

FIGURE 2. Circuit schematic of TEG

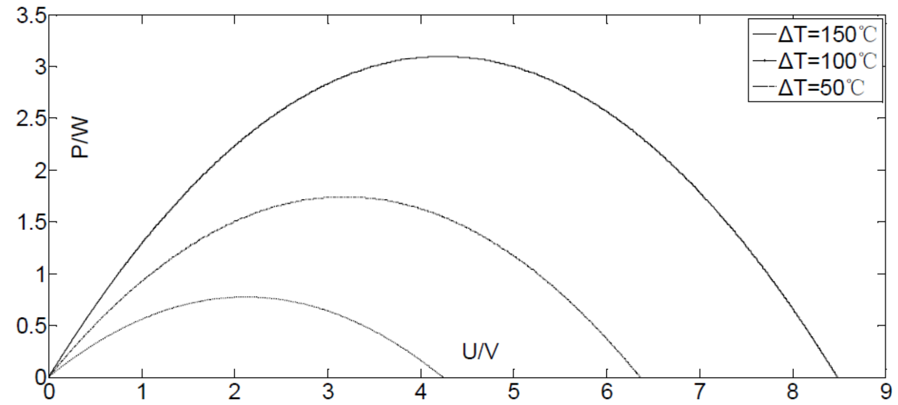

Figure 3. The P-V curve of TEG

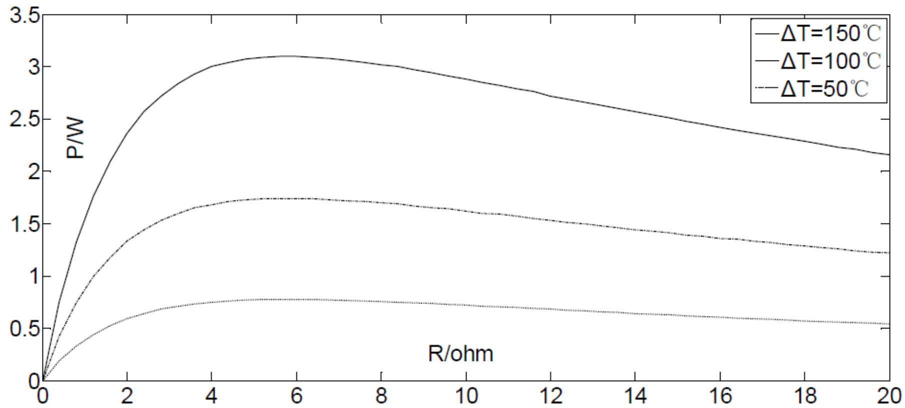

Figure 4. The P-R curve of TEG

3. **Proposed MPPT Control Algorithm.**

3.1. **The improved variable step of MPPT algorithm.** Based on the P-V curve of TM, the improved algorithm is proposed in this paper. The curve is divided into a, b, c regions. As shown in Figure 5, the output power changes large along with the change of output voltage in the area c, and then the relatively larger step size is given for perturbation. When it comes to area b, the change of the power becomes smaller, and a relatively smaller step is used. After reaching steady-state, there is a small range of shocks at the MPP because of the sampling and parameter setting. To improve efficiency and reduce oscillation, a tiny step size is used for tracking. In addition, this algorithm also proposes a regional limited method when the working point is approaching to MPP. This method will improve stability of steady-state and make a good response to the change of system.

The flow chart of the proposed algorithm is shown in Figure 6. After entering the interrupt, ΔU, ΔP can be calculated by sampling the voltage and current. If the slope of the curve's point is k_n and $k_n = \Delta P_n/\Delta U_n$, the symbol of $M' = k_n * k_{n-1} = (\Delta P_n/\Delta U_n)*(\Delta P_{n-1}/\Delta U_{n-1})$ will decide whether the system is working around the MPP or not. However, this formula has the situation of zero denominator. In order to avoid this situation, the formula of $M = \Delta P_n * \Delta U_n * \Delta P_{n-1} * \Delta U_{n-1}$ is proposed. It has the same symbol with M', but without denominator. When the value of M is greater than zero, the current working point must be away from the MPP and a larger step size which equals N_1 is set for perturbation. When the value of M is smaller than zero, the current working point must cross the MPP, and a smaller step size is set for accurately tracking. When the value of M' is zero, it means the system is working on the MPP and the

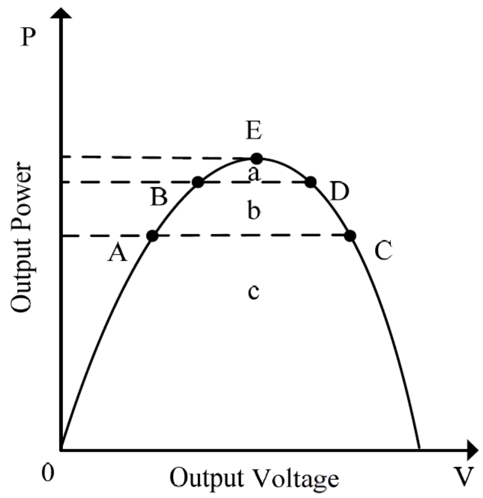

FIGURE 5. Schematic diagram of P-V curve

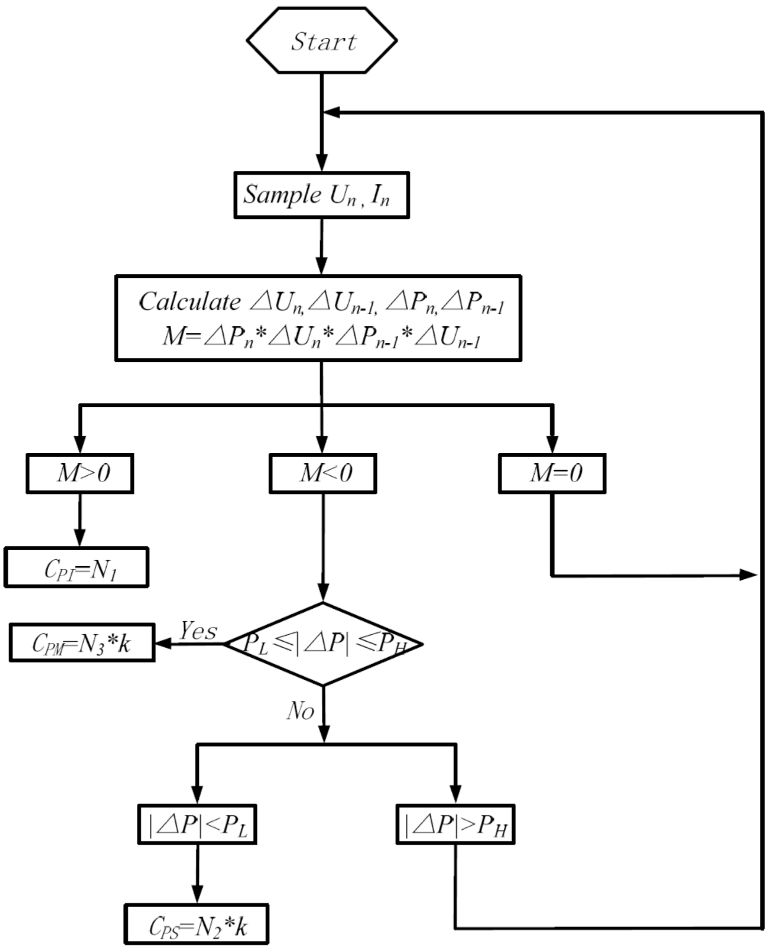

FIGURE 6. The flow chart of the proposed algorithm

statement will be kept as before. When the value of M is smaller than zero, a judgment about the absolute value of ΔP ($|\Delta P|$) is introduced. If the absolute value of ΔP ($|\Delta P|$) is smaller than P_L which is set as 3W in this paper, it means the work before goes well, and the fluctuation on the MPP is treated as permission. So a smaller step $C_{PS} = N_2 * k$ is set for stabilization, where N_2 is a constant and k is the slope. If $|\Delta P|$ is larger than P_L, but smaller than P_H which is set as 10W in this paper, it means that the fluctuation has broken the limit of permission but never dramatically, which is considered as small interferences and the step $C_{PM} = N_3 * k$ will be set, where N_3 is a constant. If the $|\Delta P|$ is larger than P_H, it sends the signal that the output power of system undergoing large-scale changes and the MPP changes as well. It need renew the whole algorithm. Because of the utilization of regional limited loop, the system can pursue optimization efficiently.

3.2. **The regional limited method.** In the proposed variable step algorithm, the setting of power limited loop has an important influence on system's steady-state. In order to improve the tracking efficiency at MPP, this paper presents a method of power limited loop which deals with the power fluctuation by increasing the judgment of power changing.

As shown in Figure 7, there is a power fluctuation at the MPP and the value of the fluctuation is limited in this method. Generally, the fluctuations of algorithm or samping at MPP are located in region a, and 3W as the value limitation can be set in this paper. If the fluctuations in the region b, it indicates that a slight change happening in the outside such as changes in temperature, and the output power deviates from MPP but not far away. According to engineering experiences, this paper sets deviation limitation as 10W. If power fluctuations locate in region c, which indicates that the system undergoes a large-scale change, the output power far deviates from MPP. When the system enters the next stable MPP, the power of the region will be re-divided into a', b', c' regions. The different settings of step size in each region will promote the tracking speed effectively.

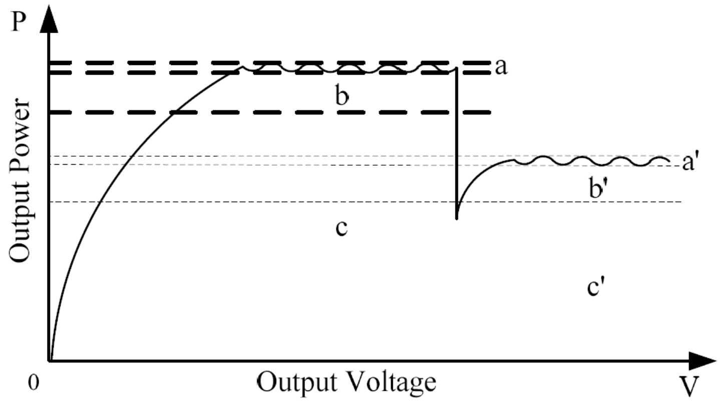

Figure 7. The dramatic change at MPP

4. **Simulation Results.** In the MATLAB, a 200W TEG system is selected to be simulated and to verify the proposed MPPT algorithm. The output power of the traditional algorithm at MPP is shown in Figure 8, and the results of the proposed algorithm is shown in Figure 9. It is obvious to see that the proposed algorithm reduces the power fluctuation significantly.

Besides, the rapid change of system has also been simulated. In Figure 10 and Figure 11, when time reaches 0.2s, the temperature will reduce from 230°C to 150°C; when time reaches 0.3s, the temperature will increase from 150°C to 230°C. The output power of traditional P&O algorithm is shown in Figure 10, and the output power of the proposed algorithm is shown in Figure 11. According to the simulation results, we can get the conclusion as follows. Firstly, the dynamic convergence speed of the system using the proposed algorithm is increased significantly. The traditional P&O algorithm needs 0.045s to arrive at MPP, and the proposed algorithm needs only 0.01s. Secondly, the fluctuation of the traditional algorithm is obviously higher than the improved algorithm at MPP, which means that the accuracy of the proposed algorithm is higher. Finally, the proposed algorithm can reach MPP faster when the system undergoes a rapid change.

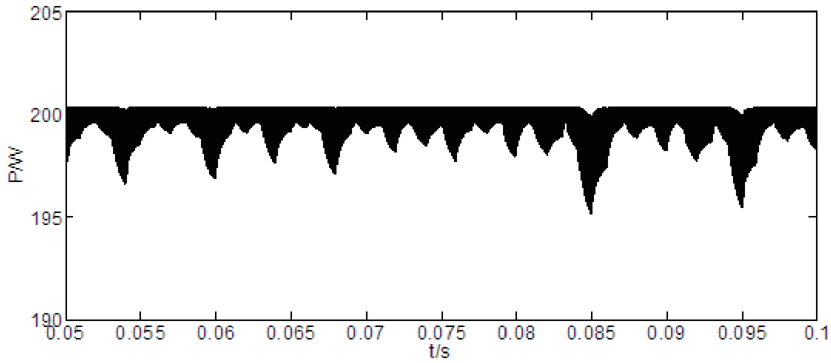

FIGURE 8. The output power at MPP with traditional P&O algorithm

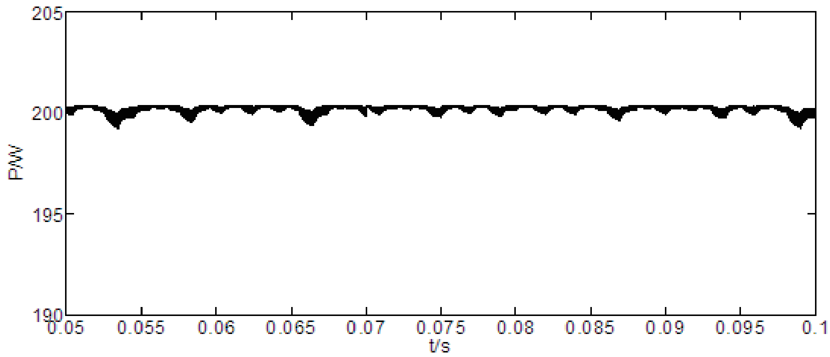

FIGURE 9. The output power at MPP with the proposed algorithm

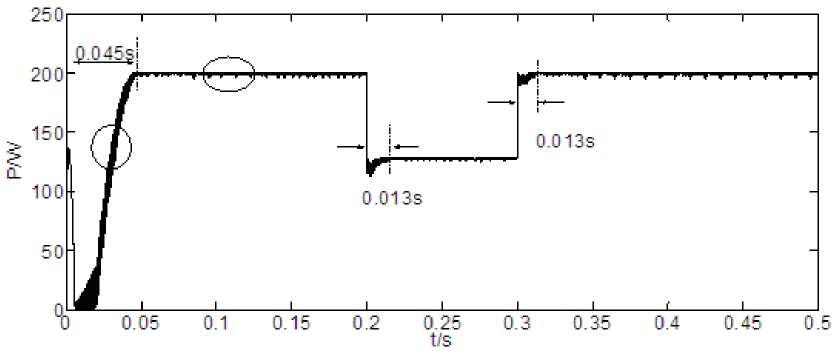

FIGURE 10. The output power with traditional P&O algorithm

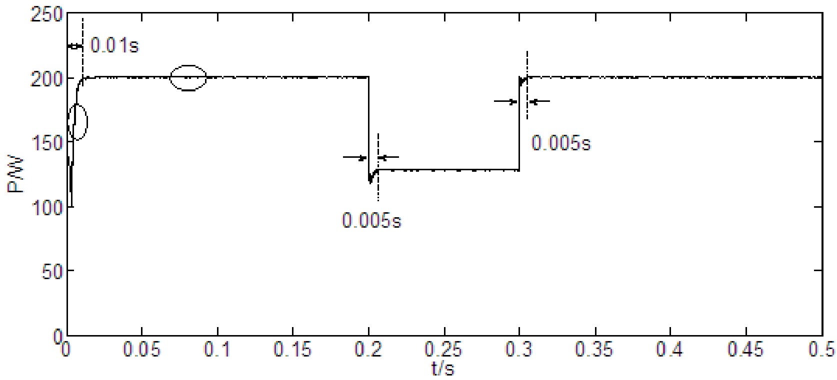

FIGURE 11. The output power with the proposed algorithm

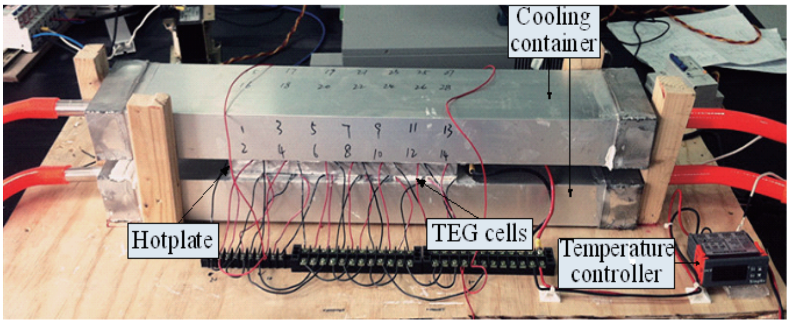

FIGURE 12. The experiment platform of TEG system

The experiment platform of TEG system is shown in Figure 12. It mostly consists of TEG cells, hotplate, cooling container and temperature controller.

5. **Conclusion.** In this paper, a new control algorithm has been used to track MPP of TEG system. The proposed MPPT algorithm can make a judgment by the absolute value of the power change and adjust step size automatically. Experimental results show that the proposed method has better performance in both dynamic-state and steady-state. In our future work, more practical experiments will be carried out based on the proposed MPPT algorithm, and the better methods will be researched to combine the existing algorithms to the real conditions.

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