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Research Article

Electrical Performance Analysis of Thermoelectric Generator HZ-20 with particle swarm optimization Algorithm

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ABSTRACT

Introduction: The Thermoelectric Generator (TEG) represents a recent development renewable energy technologies, harnessing heat energy to generate electricity from various waste energy sources. the maximum power point (MPPT) is an essential approach to maximizing energy extraction from thermoelectric generators. the position of this point is not fixed but it moves according to the difference temperature and load. Many classic methods and controllers have been widely developed and implemented to track the maximum power point. The Perturb and Observe algorithm was chosen, due to its simplicity and convergent capacities. However, the operating point oscillates around the MPP that increase the loss of energy in the power of the TEM.

Objectives: of the paper is a comparative analysis of an optimization technique Particle Swarm Optimization (PSO) along with Perturb & Observe (P&O) for the extraction of maximum power from the thermoelectric generator.

Methods: Particle Swarm Optimization PSO is based on two fundamental principles: the retention of information on past performance, and communication between the agents forming the swarm. The chosen DC-DC converter approach, a one directional boost converter, is used in combination with the MPPT approach to construct the power conditioning unit. The TEG modeling was integrated with the Perturb and Observe (P&O) MPPT technique and the Particle Swarm Optimization (PSO) MPPT method.

Results: In this paper we will evaluate the performance of PSO and P&O algorithms for maximum power point tracking with thermoelectric generator connected to load via Boost converter is verified on MATLAB/Simulink environment. The simulation results shows that the two techniques defeat the maximum power problems and the Particle Swarm Optimization (PSO) method has advantages compare to Perturb and Observe (P&O) method. From this comparison it is observed that faster convergence is achieved in PSO algorithm when compared to P&O algorithm.

Conclusions: Key contributions include methodological improvements such as dynamic adjustment of the cycle for boost converter and a new approach to partner selection, which significantly optimizes the algorithm's performance. This research provides a robust framework for thermoelectric generator parameter extraction, offering practical benefits for thermoelectric system designers and researchers in improving model accuracy and efficiency.

Keywords: thermoelectric generator, perturb and observ , particle swarm optimization.

INTRODUCTION

Renewable energy is energy derived from natural sources that can be renewed like solar, wind and thermoelectric power. When the world energy demand increases, renewable energy has become highly important in the world that based on the fact that conventional resources are unsustainable practice on the long term. Thermoelectric energy is renewable source of energy, are able to convert the heat energy to electrical power. The thermoelectric generator consists of a number of thermocouples that are connected electrically in series to increase the voltage and thermally in parallel [1], as example, the HZ-20 module which it consists of 71 thermocouples . The main challenge facing the output power of the thermoelectric generator is the instability which is affected directly by the temperature applied. Such as most renewable energy sources like photovoltaic cells and wind turbine, TEG depends on the operating conditions. Therefore, a TEG system needs a control algorithm to transfer the maximum generated power continuously to the load at any operating condition. There are several algorithms that were reported for MPPT in photovoltaic (PV)systems, and most of these techniques can be used in TEG systems [2]. [3] did analytical modeling and simulation of Peltiers and Seebeck generator modules. The analysis was done in terms of the main parameters needed for quick evaluation. These included current, voltage, thermal resistivity, and efficiency. B. Bijukumar et al[4] developed a controller to modulate the current of a grid-connected inverter, where the supply source is an array of TEGs. The design involved a TEG array, boost converter, and three-phase voltage source converter connected to a grid. A. Belkaid et al[5] modeled a TEG with an MPPT technique. The MPPT uses a sliding mode control to a boost converter. This technique is compared to a Perturb and Observe (P&O) MPPT algorithm. The results showed that the efficiency of this technique is more than 2% higher than the P&O algorithm. From the cited MPPT methods, the Perturb and Observe (P&O) method is the most adopted for TEG systems at present. These MPPT algorithms are extensively employed and perform well due to their easy and low-cost implementation as well as for their high tracking accuracy. The main disadvantage of this algorithm that when the MPP is reached, the output power oscillates around the MPP. Therefore, resulting in a power loss in the thermoelectric system[6]. To overcome the aforementioned problems, new metaheuristics algorithms are proposed in the literature. Among them, artificial bee colony (ABC), genetic algorithm (GA), Whale Optimization (WO), cuckoo search (CS). In this paper, a particle swarm optimization (PSO) is proposed . The PSO algorithm is a non-linear technique that draws its inspiration from the behaviors observed in birds, fish and bees. This approach is widely applied in various fields of engineering and science to optimize processes and design efficient systems. PSO is based on two fundamental principles: the retention of information on past performance, and communication between the agents forming the swarm. By combining these two principles, PSO offers an elegant solution to complex optimization problems.

Among PSO based approaches, some have demonstrated notable efficiency in terms of MPPT, underlining the robustness of this metaheuristic under varying conditions. We employed MATLAB/Simulink for the performance assessment of our proposed method.

The goal of the paper is a comparative analysis of an optimization technique Particle Swarm Optimization (PSO) along with Perturb & Observe (P&O) for the extraction of maximum power from the thermoelectric generator.

The performances of P&O and PSO techniques were compared for different variation of difference temperatures of the generator. A detailed and rigorous mathematical model along with simulation results and its performance for maximum power extraction from the generator were analyzed by using P&O and PSO.

Subject of investigations. In most practical applications, the different temperature applied on the TEG module sides is not constant, as a consequence, the electrical output voltage of the module is affected directly by these changes and doesn’t work or extract the maximum power. To overcome this problem, the external load must be connected with the TEG module (HZ-20) via a DC-DC boost converter integrated with a MPPT control algorithm (PSO) to adjust the load resistance with the internal resistance and maximize the harvested output power at any variation in temperature at different operating conditions.

MODELING A THERMOELECTRIC GENERATOR

Thermoelectric generator (GTE) which consists of several thermoelectric thermocouple, comprising a p-type and n-type material connected electrically in series and thermally in parallel. Heat is applied into one side of the pair and rejected from the opposite side. An electrical current is produced, proportional to the temperature gradient between the hot and cold junctions.

A typical thermoelectric generator power module is shown schematically in Figure1: Taking the HZ-20 module as an example, rated for 19W at ΔT=200°C. It consists of 71 thermocouples connected electrically in series and thermally in parallel[7].

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Figure 1 . HZ-20 Thermoelectric generator.

The open-circuit thermoelectric potential V_{OC} can be expressed as:

$$V_{oc} = \alpha \Delta T \quad (1)$$

Where;

α: is the Seebeck coefficient.

ΔT: difference of the temperature between the two side of the generator.

The Norton equivalent circuit of a practical TEG is shown in Figure 2 [5].

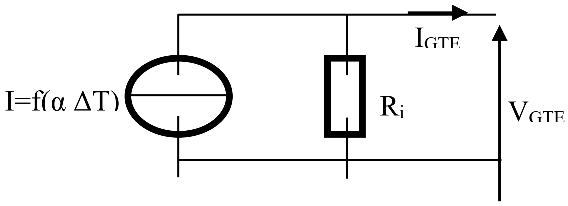

Figure 2. Norton equivalent circuit for TEM.

The output current I_{GTE} of GTE generator is given by:

$$I_{GTE} = \frac{N_S.\alpha_{pn}.\Delta T - V_{GTE}}{N_S R_i} \quad (2)$$

Where Ns number of TE thermocouples connected in series, and R_i electrical resistance of GTE.

Characteristic of the thermoelectric generator HZ-20

Simulation model for the GTE HZ-20 has been developed in MATLAB simulink software. For this simulation work the thermoelectric generator datasheet used has been presented in Table.1.

Table1: Electrical characteristics data of GTE HZ-20 taken from the datasheet.

Property	value
Width and length	7.5cm
Design hot side temperature	230°C
Design cold side temperature	30°C
Maximum continuous temperature	250°C
Power and matched load	19watts
Load voltage	2.38volts
Internal resistance	0.2981ohm

Figure 3 illustrates the output power generated as a function of current for the HZ-20 TEG module. It is evident that the output power increases with an increasing temperature difference.

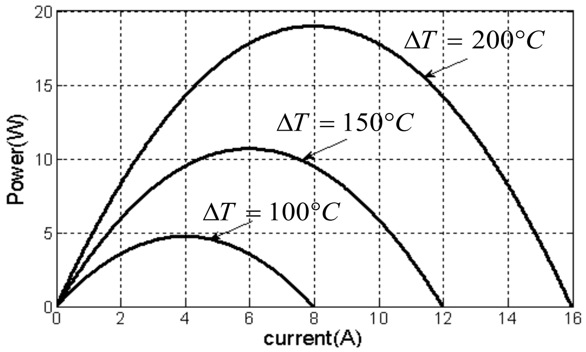

Figure 3. P-I Characteristic of the module or different temperature gradients.

The GTE will not automatically operate at the MPP due to variations in different temperature gradients. Maximum Power Point Tracking (MPPT) is employed to continuously track the MPP, ensuring that the TEM module operates at the MPP at all times.

MAXIMUM POWER POINT TRACKING FOR THERMOELECTRIC SYSTEM.

A maximum power is extracted from the TEG when a specific load value is connected to its terminals. This defined value varies with the internal resistance of the TEG. MPPT control algorithms are employed with DC-DC converters to optimize the impedance matching between the TEG and the load, ensuring that the TEG consistently operates at the maximum power point (MPP), two MPPT techniques were studied in this paper: perturb and observe (P&O) and Particle Swarm Optimization (PSO). In the following subsections, a concise overview of the two MPPT methods utilized for our TEG systems will be presented.

The synoptic scheme for any MPPT control approach of TEG systems is presented in Figure 4.

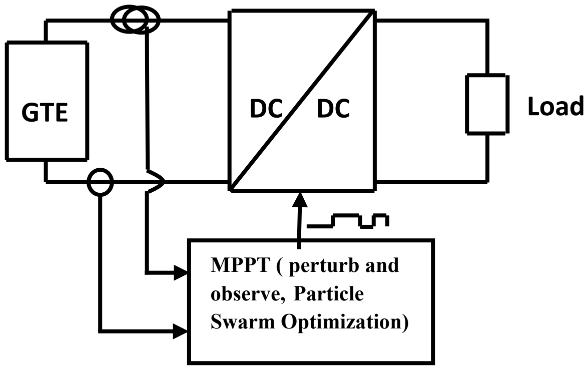

Figure 4. MPPT control scheme of a TEG system.

BOOST CONVERTER DESIGN

Fig. 5 illustrates the Boost converter circuit diagram; it can able to regulate the voltage level at load terminal. The output voltage is related to the input one as follows [7]:

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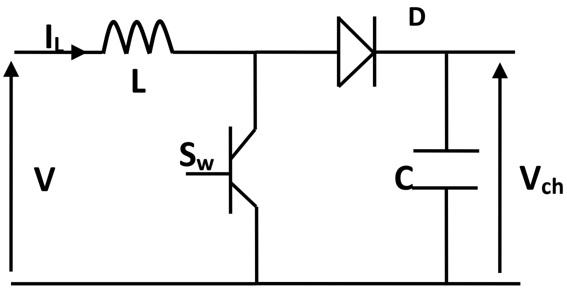

Fig. 5. basic boost converter circuit.

$$\frac{V_{ch}}{V} = \frac{1}{1-\mu} \qquad (3)$$

Where:

V: is TEM output voltage in (V).

Vch: is the converter output voltage.

μ : is the converter duty cycle as a switching command signal.

The dynamic model of the Boost converter circuit is:

$$\begin{cases} \dfrac{dV}{dt} = \dfrac{1}{L}(1-\mu)x_2 + \dfrac{1}{L}V \\ \dfrac{dI_L}{dt} = -\dfrac{1}{R_{ch}}x_2 + \dfrac{1}{C}(1-\mu)x_1 \end{cases} \qquad (4)$$

PERTURB AND OBSERVE METHOD (P&O)

Simplest in its algorithm and easy to implement on any microcontroller makes this P&O MPPT a user friendly, allowing most authors to implement for their applications. The P&O method operates by calculating the output power and introducing a perturbation (increase or decrease) that affects the system's output power.

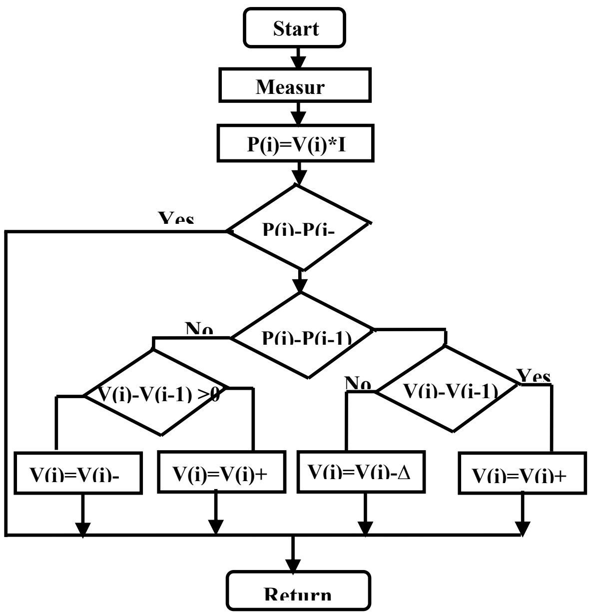

Fig. 6 basic boost converter circuit.

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This is done by sampling the TEG's current and voltage. If the perturbation results in an increase in output power, the voltage is increased to further approach the MPP. Conversely, if the perturbation causes a decrease in output power, the voltage is decreased. This adjustment results in a change in the duty cycle, and the process is repeated until the MPP is reached [8].However, the drawback of this technique is that the operating point of the TEM oscillates around the MPP. Therefore, the power loss may increase.

PARTICLE SWARM OPTIMIZATION

Particle swarm optimization is a novel approach for solving optimization problems. In this algorithm, entities known as particles are distributed throughout the search space of the function to be optimized. Each particle evaluates the value of the cost function at its specific location within this space [8].

In the PSO method, the motions of the particles are a direct result of adding three components such as global - search, local search, and the previous traveled distance which is multiplied by a set of certain weighting coefficients. In this case, the method to search for the particle could be modified by manipulating the weighting coefficients, but it is better to conduct a wide global search first, and then a local search around the most likely location[9] .

The position of a particle is influenced by two variables: the best solution found by the particle itself (pbest), which is stored for use as individual best position, and the best particle in the neighbourhood (gbest), which is stored as the best position for the swarm[10],[11].

PSO optimization depends on two main equations of velocity and position.

$$v_i^{(k+1)} = w \times v_i^{(k)} + c_1 \times r_1\left(x_{ibest} - x_i^k\right) + c_2 \times r_2\left(x_{gbest} - x_i^k\right) \quad (5)$$

$$x_i^{(k+1)} = v_i^{(k+1)} + x_i^k \quad (6)$$

where: v_i^k is previous velocity of particle, v_i^{k+1} is updated velocity after each iteration, x_i^k is previous position of particle, x_i^{k+1} is updated position after each iteration, x_{ibest} is personal experience of each particle, x_{gbest} is social experience of whole swarm, w is the inertia weight, c_1 and c_2 are acceleration coefficients, r_1 and r_2 are random numbers between [0 ,1].

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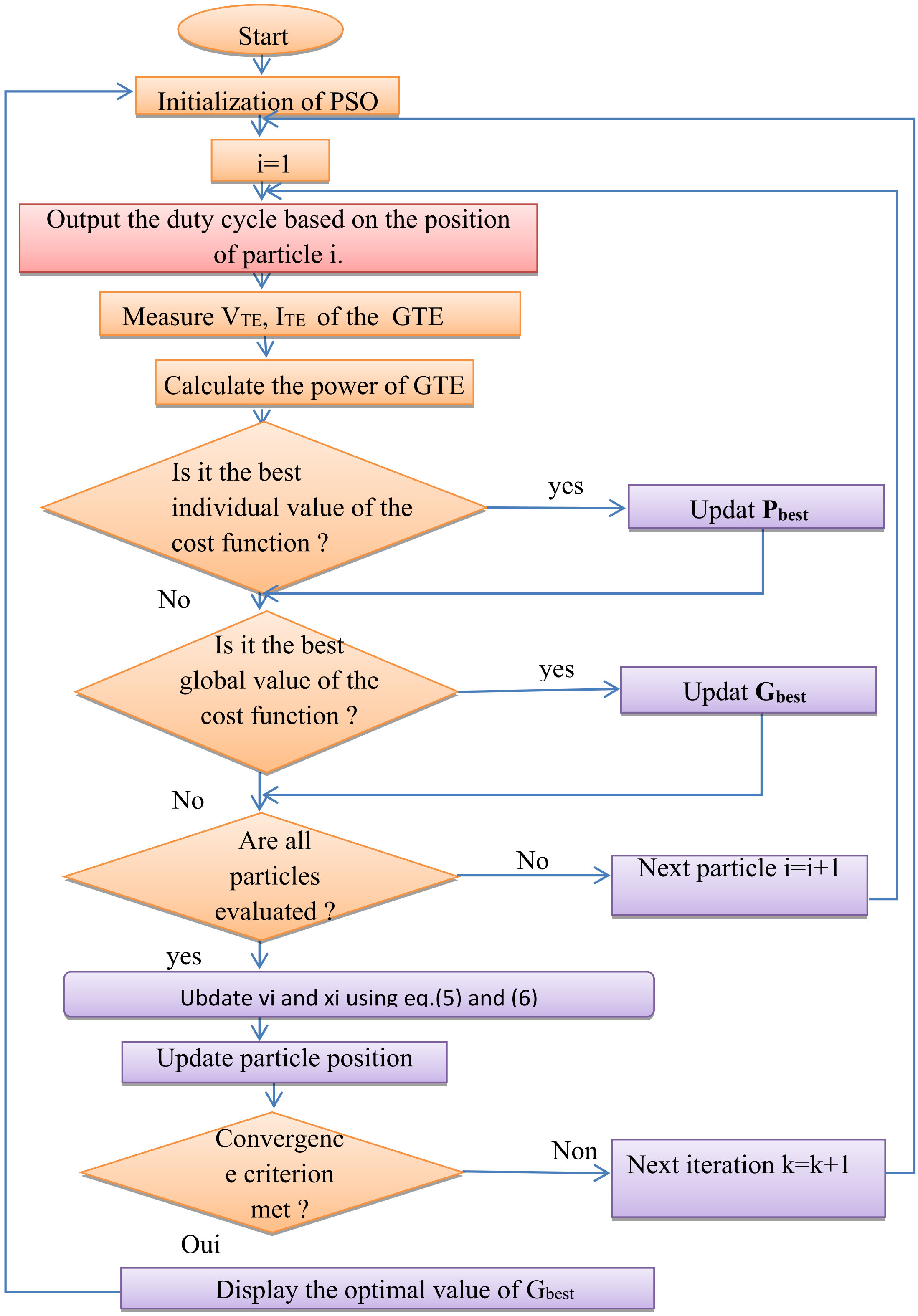

Fig.7 illustrates the algorithm of PSO method

SIMULATION RESULTS AND ANALYSIS

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the proposed system that was simulated in Matlab, in which the terminal voltages of the thermoelectric generator was controlled by the DC-DC t converter and its output was coupled to the load. The switch of the converter was controlled by different MPPT algorithms and their tracking efficiency were analyzed and compared under various conditions.

Simulation result of GTE for the different temperature gradients $\nabla T = 200°C$ and constant load R_{ch}=3Ω.

The results of the output power, voltage and current of the TME for the different temperature gradients $\nabla T = 200°C$ are depicted in Figure8, Figure 9 and Figure 10.

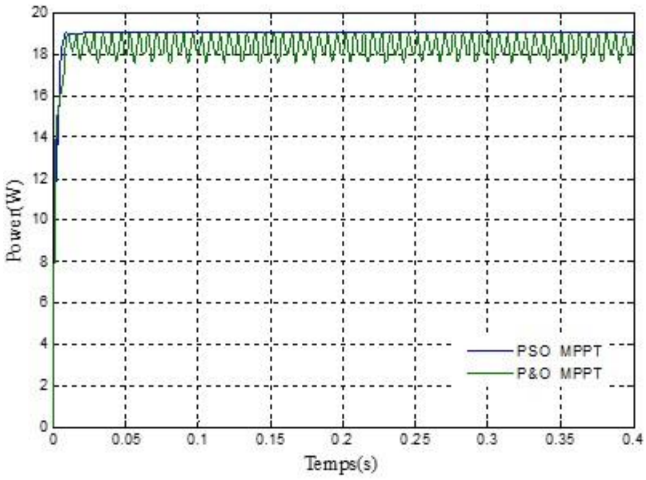

Fig. 8. GTE Output power

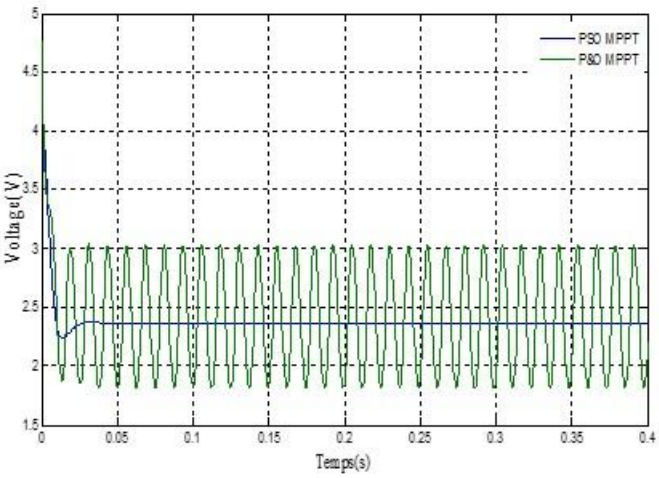

Fig. 9. GTE Voltage

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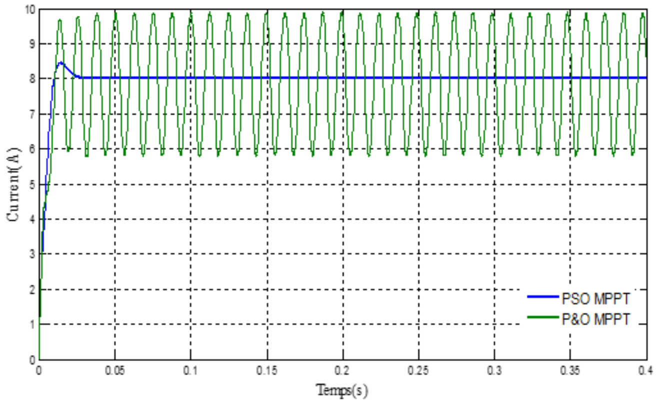

Fig. 10. GTE Output Current.

From the simulation results, we can observe in figure 8 that the PSO shows the best performance in both the total power (less steady state oscillations) and the response time (faster settling time) against the P&O ,resulting in higher energy produced by the GTE generator. the figure 9 and Figure 10 show the output waveforms of the voltage and current, The results illustrates that the PSO MPPT reaches faster to the optimal voltage and current with less oscillations compared to the both MPPT.

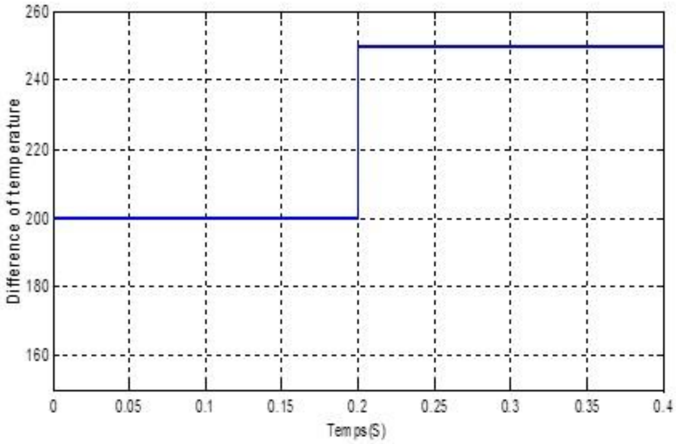

Fig. 11. Variation of temperature difference.

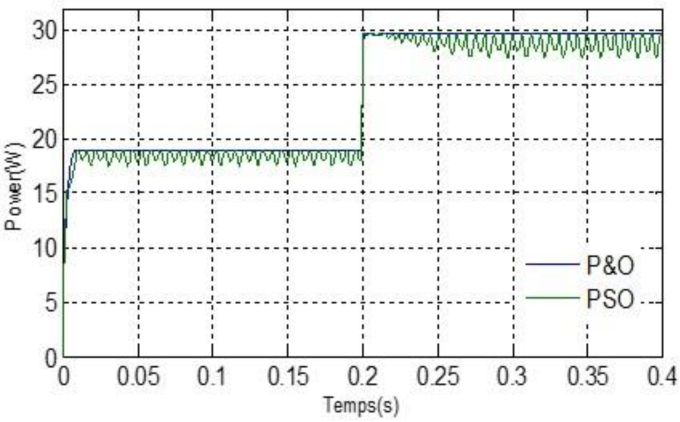

Fig. 12. GTE Power Output

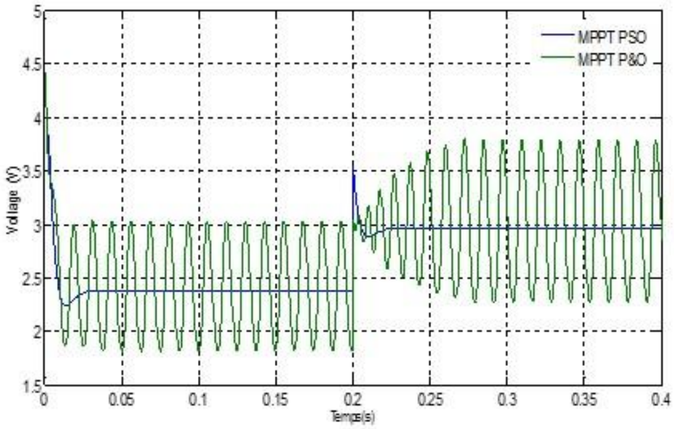

Fig. 13. GTE Voltage Output

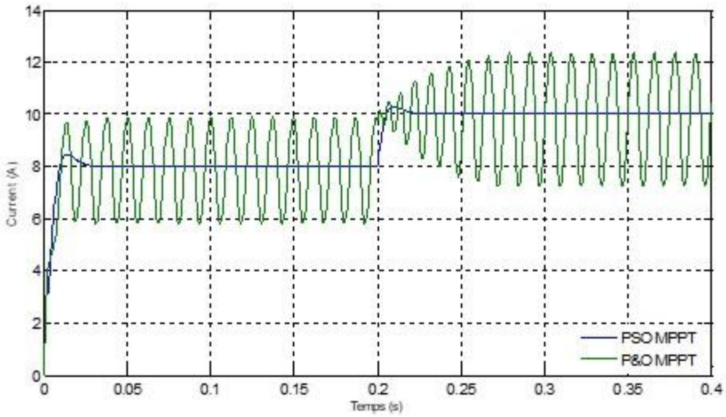

Fig. 14. GTE Current Output

The PSO is tested under varying temperature to verify its effectiveness. The system in Figure 11 is set to operate at constant load while the temperature is varied. Initially, the temperature is set at 200 °C and gradually increased to 250 °C.

Figure 12 shows the power output from the system utilizing PSO and P & O MPPT algorithms. It is noted that the increase in power is the result of increasing of the differential temperature between the TEM. We observe that the obtained characteristics curves, especially the power ones, show that the tracking speed of PSO MPPT is faster than P&O.

On the other hand, in the same figure, we can note that for a change in the level of differential temperature between the TEM (ΔT),the two algorithms let the TEM work at its maximum power, but, the P&O oscillates more than the PSO one.

Furthermore, when the temperature differential between the TEM suddenly varies from 200°C to 250°C at 0.2S, it can be observed that the power loss caused by P&O MPPT is 1W compared with PSO is 0W. We notice that the PSO MPPT has a good steady state performance under the differential temperature variations.

In Fig. 13 and Fig. 14 shown that the voltage and the current of the operating point are reduced under PSO. From the Simulations results, it is confirmed that the power loss of the proposed method is lower than that of conventional P&O MPPT.

CONCLUSION

This study proved that employing the PSO method for MPPT significantly enhances the power generation and efficiency of TEGs. Commercial HZ-20 TEG module connected to a DC-DC boost converter with PSO MPPT has been simulated, implemented and tested at different operating conditions.

From the results, it can be concluded that the proposed TEG testing system with the PSO-MPPT method can achieve the maximum output power of the TEG module with good accuracy, low fluctuation around the MPP at rapid changes of temperature and at any operating condition and give maximum efficiency 99% for the simulation results than a conventional P&O MPPT algorithm.

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