Improving the Performance of the MPPT for Thermoelectric Generator System by Using Kalman Filter

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Abstract—**In this paper, perturb and observe (P&O) algorithm is presented to grab the maximum power point from Thermoelectric Generator (TEG) sources. The main contribution of this study relies on estimating the output power of TEG by using Kalman filter to readjust the characteristics of TEG with respect to operating conditions. In the real applications, there is a disturbance appears on the power curve due to the heat distribution on the TEG surfaces. For smooth implementation of the maximum power point tracking (MPPT) algorithm and to overcome the disturbance, Kalman filter is used. It is estimate the output power curve which paves the way for MPPT to be implemented easily in the microcontroller. The feasibility of the proposed harvesting system verified experimentally.**

Keywords-thermoelectric generator (TEG); maximum power point tracking (MPPT); Kalman filter; energy harvesting system

I. INTRODUCTION

One of the new disciplines attracting the attention of scholars is the renewable energy sources with a special focus on converting the waste heat energy into electric energy. Recently, thermoelectric generator (TEG) devices have paved the way to recover the waste heat energy which occupies a great deal of research to assess the scope of renewable energy sources. Furthermore, this source is very friendly to the environment. It has the advantages of no pollution, no noise, and limited maintenance etc.

Reference [1] points out several useful applications which use TEG devices to recover the waste heat energy and shows the flexibility of these devices to work in transport, residential and industrial revivals. For instance, in the automobile, the waste heat increases up to 35% of the fuel consumption which reflects a suitable environment to use TEG devices and utilize this huge waste of energy.

Because of the natural behavior of TEG devices, there are several issues appear in the practical applications such as power mismatch loss and the operating conditions. The change of the internal resistance in these devices happens according to the change in the temperature difference. That change is considered as a core issue which causes a mismatch in the system [2] and disallows the system to be operated at the maximum power. For the large-scale TEG applications, a mismatch might appear due to the heat distributions on both sides of the TEG devices i.e. cold and hot side which cause power reduction. On the other hand, the maximum power point tracking (MPPT) algorithm should be implemented in order to overcome the power reduction in the energy harvesting system, especially when the system has a vast temperature distribution. An efficient MPPT can easily interface TEG with a load by choosing the right DC-DC converter to extract the optimum power operation.

There are several MPPT algorithms proposed for the photovoltaic system that works similarly with TEG systems. These algorithms such as Perturb & Observe (P&O) [3]-[6], Incremental Conductance (INC)[6], the fractional current and voltage techniques [7] are able to interface between TEG array and the load sink.

Fig. 1 illustrates the proposed energy harvesting system which consists of TEG array, a boost converter, and a resistive load was implemented in the laboratory. Furthermore, a common MPPT schemes Perturb & Observe (P&O) was implemented to grab optimum power under various temperature difference. To overcome the disturbance which appears on the output characteristics and for easy implementation of Perturb & Observe algorithm, Kalman filter was utilized in STM32f429 microcontroller.

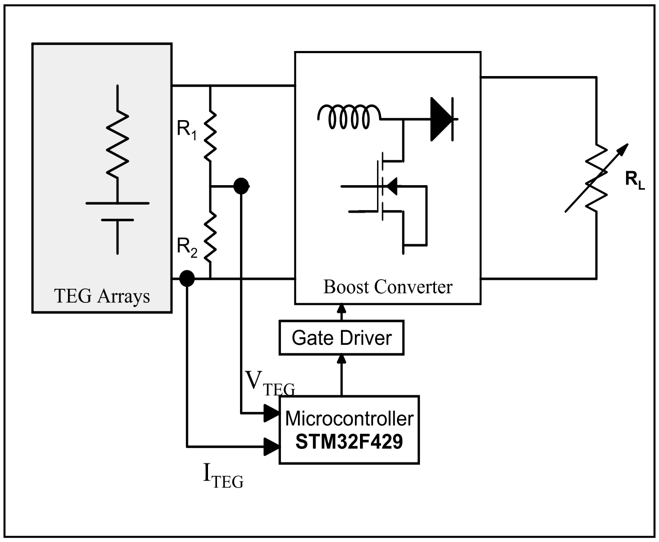

Figure 1. The Proposed Energy Harvesting System.

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II. THERMOELECTRICAL GENERATOR MODULE

Due to a temperature difference (ΔT) which is imposed on two different materials joined together to form thermocouples, a potential voltage is produced. TEG device consists of a number of thermocouples connected thermally in parallel and electrically in series. It is sandwiched between two surfaces made from a different material such as ceramic and aluminum. Practically, it can be mentioned that the combination of p-type and n-type pellets as a single thermocouple make a high-efficiency conversion. Fig. 2 (a) shows the thermal model and Fig. 2 (b) shows the electrical model which is presented in voltage source connected in series with a resistance.

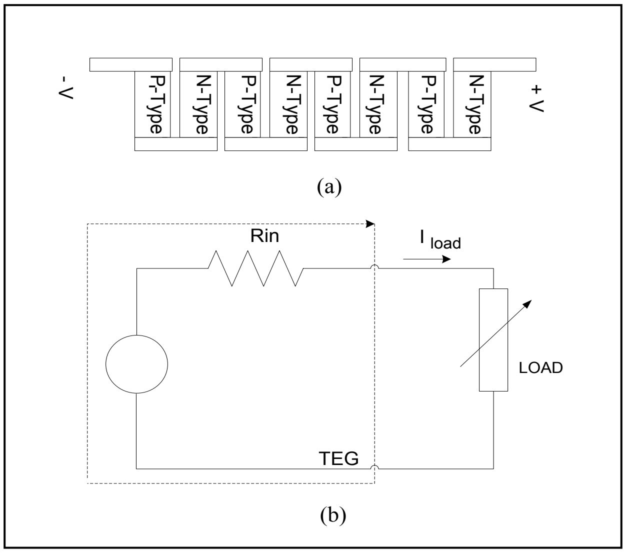

Figure 2. (a) Electrical Model and (b) Thermal Thermoelectric Generator.

The temperature difference is exposed to a number of thermocouples i.e heat source to heat the hot surface and heat sink on the cool side to remove and decrease the heat. There is an electrical potential produces between the terminals of the thermocouples which is called Seebeck effect (α). When there is no load connected to the terminal of thermocouples, the produced Seebeck voltage (Vα) can be expressed as;

$$V\alpha = \alpha \Delta T \tag{1}$$

As long as TEG device connected to a matched load R_{int}=R_L, the output voltage decreases to the half of open voltage circuit and the current of TEG (I_{TEG}) can be calculated as follow:

$$I_{TEG} = \frac{\Delta T\alpha}{R_{int}+R_{int}} \tag{2}$$

Based on the energy equilibrium concepts at the steady state, the absorbed thermal rate Q_H in the hot side and the removed thermal rate Q_C in the cold side of the TEG devices are shown in (3) and (4).

$$Q_H = \frac{\Delta T}{Q_m} + \alpha\, T_H I_{TEG} - \frac{1}{2}\, R_{int} I_{TEG}^2 \tag{3}$$

$$Q_c = \frac{\Delta T}{Q_m} + \alpha\, T_C I_{TEG} + \frac{1}{2}\, R_{int} I_{TEG}^2 \tag{4}$$

where T_H and T_C are the imposed temperature gradient on the hot side and cold side, Q_m is the thermal resistance of TEG device.

From (3) and (4), the generated power (P_{TEG}) in the TEG model can be expressed as

$$P_{TEG} = Q_H - Q_C \tag{5}$$

The efficiency (η_{TEG}) of the TEG unit is expressed in (6) which is proportional to the generated power and the absorbed thermal rate.

$$\eta_{TEG} = \frac{P_{TEG}}{Q_H} * 100 \tag{6}$$

In this study, a commercial TEG device (TEP1-142T300) is employed in the proposed energy harvesting prototype. We have characterized the chosen TEG in [2] to investigate the effect of the temperature variation on the device.

III. ENERGY HARVESTING SYSTEM

A. The Basic Construction of the System

The proposed system contains TEG array which is connected to the load through a boost converter. Boost converter was chosen because of its ability to work in a high range according to the change of the temperature difference. On the other hand, the MPPT algorithm capability of driving the converter through the generated pulse needs a noiseless power reference. Microcontroller (STM32F429) is used for the evolutional of MPPT algorithm. Fig. 3 illustrates the configuration circuit of the energy harvesting system.

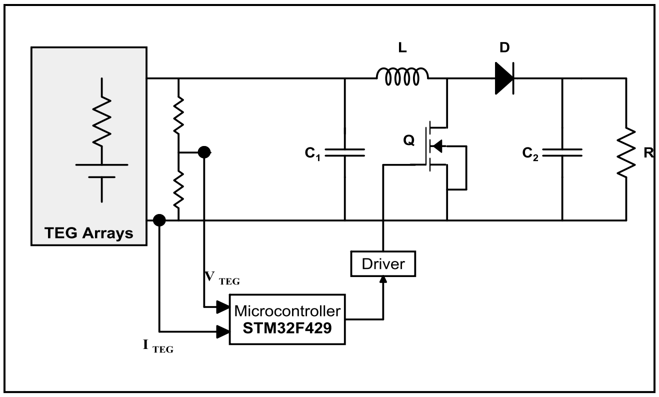

Figure 3. The Construction of the Energy Harvesting System.

B. Kalman Filter

The Kalman Filter is an optimal estimator mainly works to imprecise the data in the system linearly with noises in order to update the system foremost estimation. Moreover, the principle of Kalman filter is established on state-space method. In this process, the state equation scheme investigates the generation of noise and distortion in the signal [8].

Readjusting the output power process is carried out to eliminate the noise effects on MPPT methods. The readjusting process is done by a form of feedback control. In order to overcome the noises and the changes in operations condition, the filter estimates the power state simultaneously and accordingly, feedback is obtained. Additionally, the readjusting process is classified into two stages. The first stage concerns with measurement update as represented in predictor equations whereas the second stage indicates to the time update processes that represented in corrector equations. Based on the mentioned processes, the accurate power characteristics can be predicted without any extra equipment in the harvesting system. Fig. 4 shows the Kalman filter operation process.

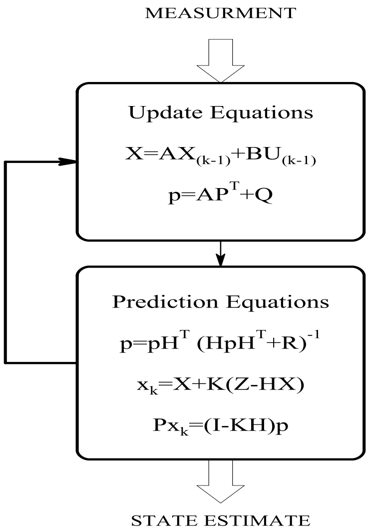

Figure 4. Kalman Filter Operation

C. *Perturb and Observe Algorithm*

The instability of the imposed ΔT on the TEG surfaces results in a change in internal resistance which exhibits in the P-V and P-I characteristics as a different maximum power point (MPP) for each temperature difference. With regard to Thevenin's Equivalent Circuit, the greatest power is generated when the load resistance is equal to the internal resistance of the source ($R_L=R_{int}$). In order to achieve this load matching, MPPT must be implemented between the load and the TEG array which lead to operating the system at MPP under various ΔT. A Perturb and Observe (P&O) algorithm was chosen for its simplicity, low cost and convergence speed.

In P&O, the output power of TEG (P_{TEG}) array is calculated from the generated voltage V_{TEG} and current I_{TEG} which is measured and readjust by using Kalman filter as illustrated in the Fig. 5. The change of temperature on the hot surface or the cold surface affects the output of the TEG array. This gives an indication that the system will not be in a state of stability and each system must have a reference power point measured in previous time ($P_{ref(k-1)}$). Then the comparison of P_{TEG} with $P_{ref(k-1)}$ must be made and a decision should be taken in the direction of disturbance concerning the affected output power by the distribution heat around the array. There are two limits to investigate the direction of climbing steps: when ΔP >0 the direction of climbing will change according to the same direction with Pref. In case, ΔP<0 the direction changes in the opposite way of Pref as shown in Fig. 6. The aim of these steps is to improve ΔP = 0 in the case of the system achieving the MPPT.

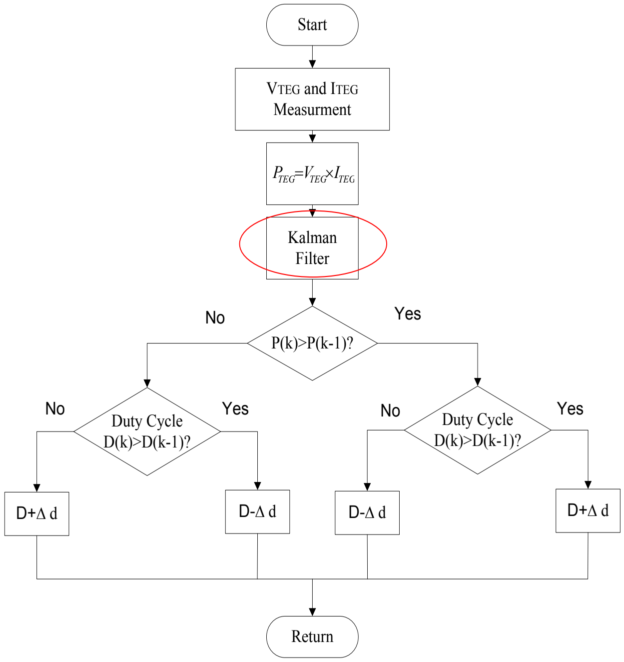

Figure 5. Flow Chart of P & O Algorithm

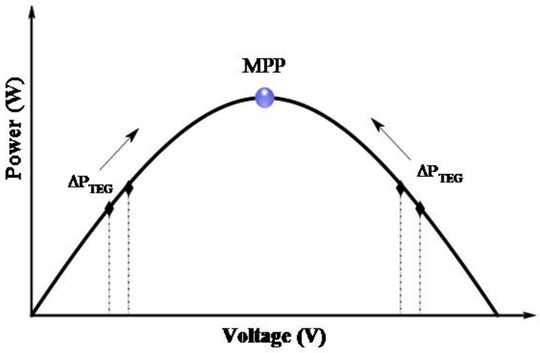

Figure 6. Perturb and Observe Technique

IV. EXPERIMENT AND RESULTS

The experiment prototype consists of three commercial TEG (TEP1-142T300) that are connected in series. The other components are a boost converter, resistive load, a voltage divider and a high sensitivity current sensor (NA250) which is a voltage-output current-sensing. In order to implement MPPT algorithm, STM32f429 discovery kit is proposed to be used for better performance. The experiment is implemented in the power electronics lab as shown in the Fig. 7.

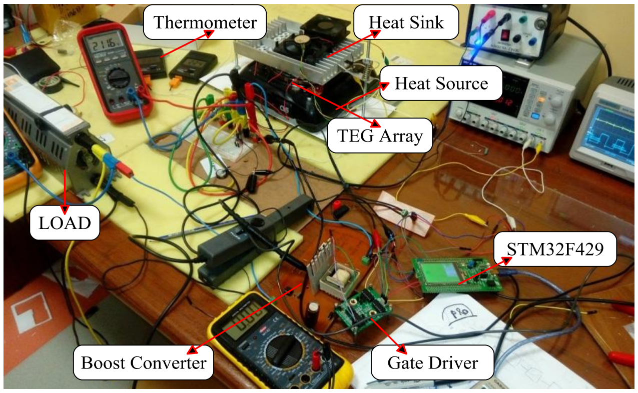

Figure 7. Energy Harvesting Prototype

Three different temperature gradients ΔT, 80°C, 100°C, 130°C were imposed on the TEG array which is connected to the proposed system to examine the efficiency of the modified MPPT algorithm under the steady-state condition. Correspondingly, the efficiency is calculated based on the output power characteristics of the TEG at the optimum point for each ΔT and the output power of the MPPT converter.

Kalman filter was implemented in the microcontroller for the output power which measured through the voltage and current sensor. This purpose is used for estimating and readjusting the output power. Moreover, this estimation allows the algorithm to climb smoothly without any confusion. Fig. 8 shows the output power of the MPPT converter.

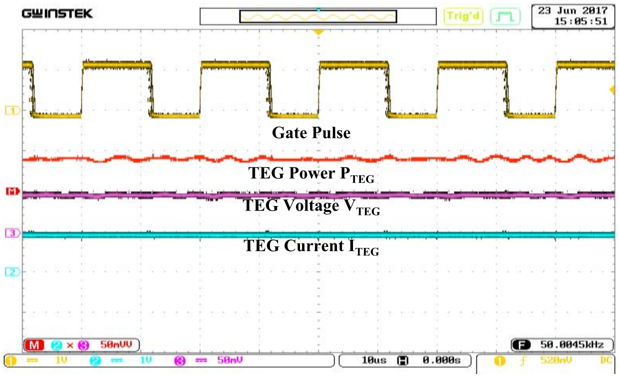

Figure 8. The Gate Driver Pulse Output Power, Current, Voltage of TEP1-142T300 with STM32F429 Microcontroller

In Kalman filter, the recursive measurement update and the time updates of processes are performed via fixing the estimation of the states.

The P&O algorithm based on Kalman filter resulted in a higher efficiency as compared to the conventional P&O algorithm. The results stated that the performance of the proposed technique is highly efficient and the MPPT efficiency has been enhanced under different ΔT as shown in Fig. 9.

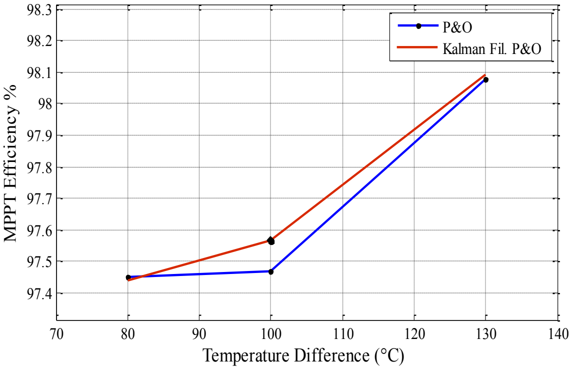

Figure 9. MPPT Efficiency vs Temperature Difference

V. CONCLUSION

In this paper, P&O algorithm was implemented based on the power characteristics readjust by using Kalman filter.

The Kalman filter was able to overcome the generated noise that paves the way to implement the MPPT algorithm. Similarly, it extracts the optimum power easily and improves the performance of the P&O especially in the noisy conditions. The results proved an obvious improvement in the performance of the P&O algorithm basis on Kalman filter. It was tested under different temperature gradient in the energy harvesting system and compared to the conventional P&O algorithm. Therefore, the proposed technique is regarded to be unique especially for large-scale applications where the heat distributions problem appears.

REFERENCES

[1] D. Champier, “Thermoelectric generators: A review of applications,” Energy Conversion and Management, Vol. 140, pp.167-181, May. 2017.

[2] K. Yahya, M. Zeki Bilgin, and T. ERFİDAN “The Effect of Temperature Variations Over Thermoelectric Generator Efficiency,” International Engineering Research Symposium UMAS2017 Duzce, pp. 192-200, 2016. Sept. 2017.

[3] O. Maganga, N. Phillip, K. J. Burnham, et al. Hardware Implementation of Maximum Power Point Tracking for Thermoelectric Generators,” Journal of Elec Materi (2014) 43: 2293. https://doi.org/10.1007/s11664-014-3046-0

[4] J. Eakburanawat, and I. Boonyaroonate “Development of a thermoelectric battery-charger with microcontroller-based maximum power point tracking technique,” Applied Energy, Vol: 83, Issue: 7, pp. 687-704, Jul. 2006.

[5] R.-Y. Kim and J.-S. Lai, “A seamless mode transfer maximum power point tracking controller for thermoelectric generator applications,” IEEE Trans. Power Electron., vol. 23, no. 5, pp. 2310–2318, Sep. 2008.

[6] G. K. Thangam, T. Rakesh and S. E. Rajan, "Performance evaluation of non-isolated high step-up DC-DC converter for thermoelectric energy harvesting system using MPPT control techniques," 2016 International Conference on Circuit, Power and Computing Technologies (ICCPCT), Nagercoil, pp. 1-8, 2016.

[7] K. Yahya, M. Zeki Bilgin, and T. ERFİDAN “Practical Implementation of Maximum Power Tracking Based Short-Current Pulse Method for Thermoelectric Generators System,” journal of power electronics. JPE. in press.

[8] Saeed V. Vaseghi, Advanced Digital Signal Processing and Noise Reduction, John Wiley, England, 2006.