TEST Engineering & Management

May – June 2020
ISSN: 0193-4120 Page No. 2156 - 2162

Enhancing the Performance of the INC Algorithm using Kalman Filter for Thermoelectric Energy Harvesting System (THES)

[1*]Khalid Yahya, [2]Nassim A. Iqteit,[3]Ibrahim Alhamrouni, [4]Mohamed Salem, [5]Mehmet Zeki BİLGİN
[1]Department of Mechatronic Engineering, Istanbul Gelisim University, Istanbul, Turkey
[2]Department of Electrical Engineering, Palestine Polytechnic University, Palestine
[3]Electrical Engineering Section, University Kuala Lumpur (UniKL BMI), Gombak 53100, Malaysia
[4]School of Electrical and Electronic Engineering, Universiti Sains Malaysia, Malaysia
[5] Department of Electrical Engineering, Kocaeli University, Kocaeli, Turkey
[1*]koyahya@gelisim.edu.tr,
[2]nassimiqteit@gmail.com,[3]ibrahim.mohamed@unikl.edu.my,[4]salemm@usm.my,[5]bilgin@kocaeli.edu.tr

Article Info
Volume 83
Page Number: 2156 – 2162
Publication Issue:
May - June 2020

Article History
***Article Received**: 11August 2019*
***Revised**: 18November 2019*
***Accepted**: 23January 2020*
***Publication**: 10 May2020*

Abstract:

improving the energy harvesting system is requiring an efficient MPPT algorithm which has the ability to track the optimum power under steady state and dynamic state. in this paper, incremental conductance MPPT was enhanced by using Kalman filter which readjusts the characteristic of the thermoelectric generator. The need of an efficient MPPT arises due to the presence of power mismatch under a various temperature gradient. this mismatching appears due to the distribution of the heat on the thermoelectrical generator surfaces. Experimentally, the influence of Kalman filter on the energy harvesting system was investigated. The efficiency of the enhanced incremental conductance algorithm was compared to the conventional incremental conductance algorithm under various temperature difference.

Keywords: *thermoelectric generator (TEG); incremental conductance algorithm;Kalman filter; energy harvesting system*

I. INTRODUCTION

waste heat is an energy which is not utilized. this energy appears in different applications especially in the automobile and the industrial areas where there is a big factory which produces Glass, Cement, Iron. as result of these productions, a huge amount of the waste heat is there. to utilize this energy, a Thermoelectric Generator (TEG) is the perfect device which has the ability to convert the thermal energy directly to electric energy based on the temperature difference.

TEG devices made from two different semiconductors sandwiched between plates which gives several advantages such as small size, easy implementation, no pollution, noiseless, low-maintenance and reliability. years ago, the use of the TEG was restricted only to Space. recently it is founded in different fields (army, medicine, transportation) where a waste heat is suitable to operate the device. for instance, in the vehicles, more than 30% of the fuel consumption consumed as waste heat energy in the exhaust gases[1]. in order to recover the waste heat, a thermoelectrical generator device is a right selection which converts the waste heat to utilizable energy. Also, there are several disadvantages hinder the use of TEG devices can be classified based on material nature and electrical nature; firstly, for the material of the TEG model, a high-efficiency device material would have a high potential voltage between its terminal which called (Seebeck potential voltage) while both electrical resistivity and thermal conductivity should be low. secondly, the mismatching that happens whenever there is a heat distribution on the device surface and causes power reduction and this happens in the begin and the end of TEG operating condition also in the large scale application whenever a big amount of TEG is used.

Electrically, an efficient Maximum power point tracking (MPPT) can overcome the power reduction that reflected from the mismatching which happens in the energy harvesting system between the source-sink and the load sink. in the literature, the used algorithms for the photovoltaic (PV) system are the same algorithms used in Thermoelectric Energy Harvesting System (TEHS) such as perturb and observe (P&O) algorithm[2]-[4], ESC algorithm[5],

May – June 2020
ISSN: 0193-4120 Page No. 2156 - 2162

open circuit voltage and short-circuit current algorithms[6]-[8].

A commercial module TEG (TEP1-142T300) made up of Bi2Te3 was selected. we test the module under various temperature difference and analyzed the effect of this variation on the internal resistance.further more, in the interest of the wide range of the temperature variation, a Boost converter is selected to interface between the TEG array and load by a generated puls regarding the modified algorithm trackin.due to the linearity of TEG characteristics, grabbing the optimal power in TEHS is more sample and easy to implement comparing it to PV system. Furthermore, the variation of the temperature is slower than irradiance makes the tracking faster.

The main aim of the paper is to extract the maximum generated power under the various condition by proposing an efficient measurement method. in this study, Kalman filter used to overcome the noise and confusion which resulted from the lake of the heat distributions. characteristics adjusting was done by Kalman filter without any external circuit, where, in the literature snubber circuit is used to overcome these noise while the recent study used Kalman filter which has zero cost. Fig.1 Shows the block digrame of the proposed TEHS.

Here the authors apply Kalman filter in Incremental Conductance algorthim (INC) for TEHS to estimate and readjust the sensed variable which implemented in the microcontroller (STM32F429). both the convenial IC algorthim and the modified algorthim was implemented in the lab where the experimental results pointed that the proposed algorithm is more efficint in comparison to the conventional INC[9]-[11].

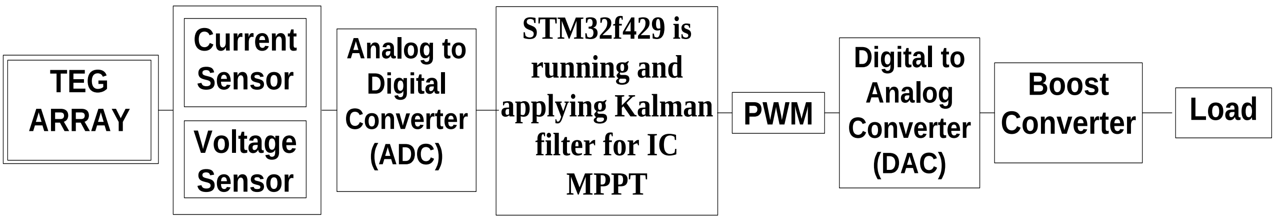
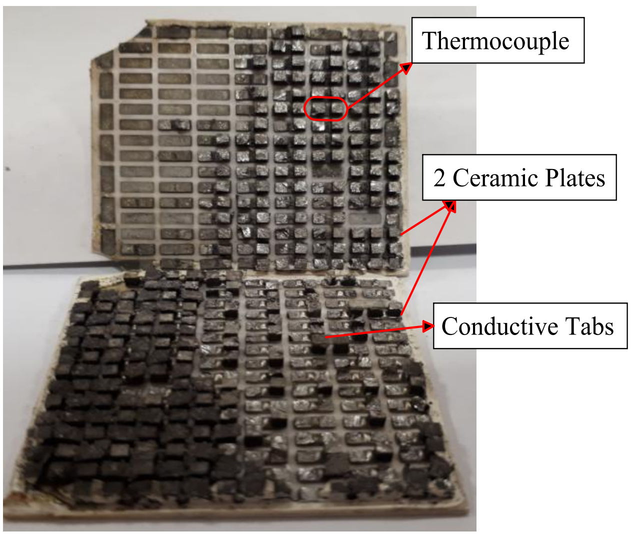


Figure 1. Block Diagram of the proposed TEHS.

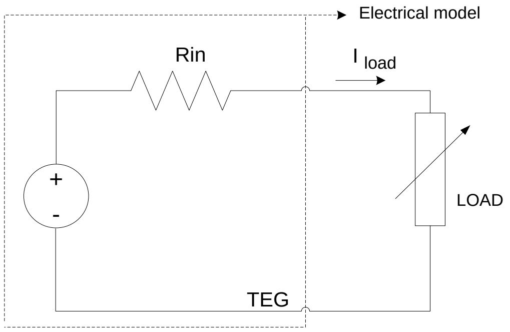
II. THERMOELECTRICAL GENERATOR MODULE

The concept of thermoelectric generation came based on a physic phenomenon which is, by applying a temperature difference for two different type metal injected together a potential energy is generated and vice versa. for a high-performance device semiconductor material (n- and p-type) are thermally linked together in parallel and formed the so-called thermocouple and inserted between two surfaces as shown in Fig.2 a. moreover, thermoelectrical generator electrically can be presented in a voltage source connected in series with a resistance as shown in Fig.2 b.



(a)

May – June 2020
ISSN: 0193-4120 Page No. 2156 - 2162



(b)

Figure 2. (a) Thermal construction (b) electrical Model of TEG

The electrical internal structure of the TEG can be defined as shown in Fig.3. P-type and N-type semiconductor legs are electrically connected to each other by a conductive tab.

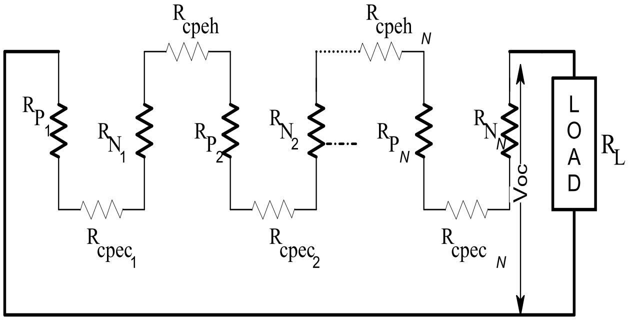


Figure 3. Electrical internal structure of TEG

Where, R_P and R_N represent respectively the electrical resistance associated with P-N type semiconductor leg.R_{cpeh} and R_{cpec} respectively, the electrical resistance of copper conductor strips on the hot side, the electrical resistance of copper conductor strips on the cold side andR_L refers to the external load resistance.N the number of the semiconductor thermocouple in TEG device which identifies the amount of absorbed thermal rate and Q_H the removed thermal rate Q_C and can be expressed as:

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

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

Where T_H and T_C are the applied temperature on the both surfaces hot cold side, $Q_m$is the thermal resistance and ΔT is the temperature difference.

III. DETERMINATION OF THETEG CHARACTERISTICS

In this study, Under various operating conditions; output power, the absorbed heat, and a thermoelectric generator (TEG) efficiency were analyzed experimentally.

TEGs series connected are arranged between the hot blocks and cold blocks in the test as shown in Fig.4. In this test, high-power electric heater powered by an AC power source was selected to heat the hot surface and the cold side is cooled by air with the help of aluminum heat sink and fan units. The output of the TEGs is connected to a resistive load.The commercial TEG (TEP1-142T300) is characterized by applying three different temperature difference ΔT: 80 ◦C, 100 ◦C and 130 ◦C.

In order to obtain precise temperature measurements, a heat sensor was placed between the fan units and the TEGs on the cold side, and another heat sensor was placed between the hotplates of the electric cooker and the TEGs and the TEG arrays were mechanically compressed by springs.

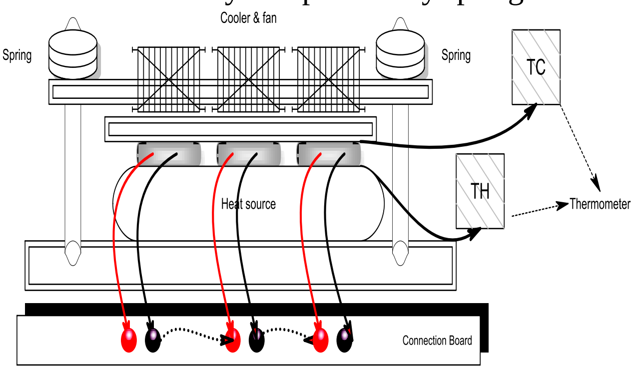
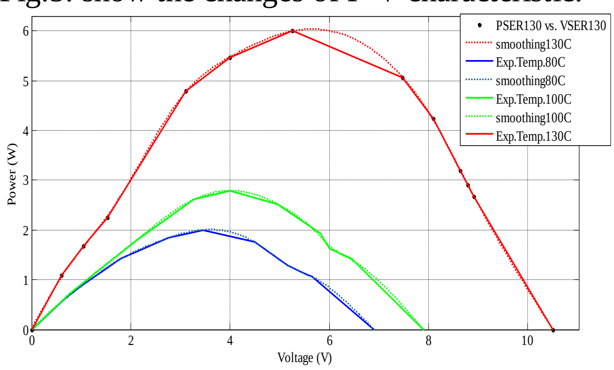


Figure 4. The schematic diagram of the test

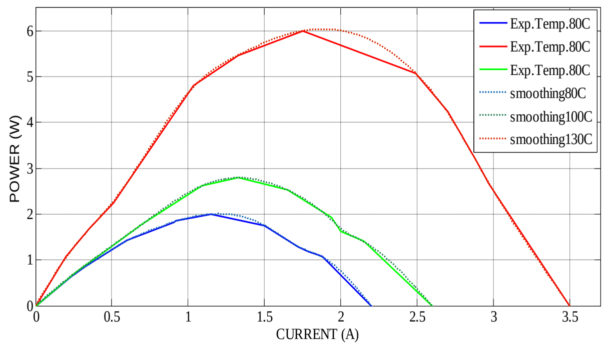
For the product coded TEP1-142T300, Consisting of 128 pairs, this module has a physical dimension of 44 × 44mm2 and has been tested at ΔT 80 ◦C, 100 ◦C and 130 ◦C.

In order to meet the requiredpower for various resistance load values and to obtain the electrical characteristics of the TEG under test correctly, the TEG devices were connected together as a series and the experiment was performed by changing the load resistance value at the same temperature difference. . Fig.5. show the changes of P-V characteristic.



(a)

May – June 2020
ISSN: 0193-4120 Page No. 2156 - 2162



(b)

Figure 5. (a) (P-V) (b) (P-I) characteristic of 3 TEGs under various ΔT

The output voltage increases by increasing the hot side temperature while keeping Tc constant. Therefore, the temperature difference increases at ΔT. Furthermore, that an increase in the hot side surface temperature also increases output power and absorbed heat. also, When the temperature amplitudes on the hot side and cold side are fixed, the average output power and efficiency can be increased to a certain degree with increasing phase angle.Fig.6illustrate the performance of TEG power generation under different Q_H thermal energy values.

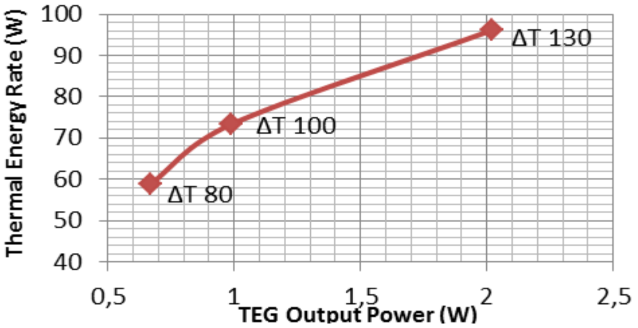


Figure 6. Output power vs. Thermal energy rate Q_H under ΔT 80◦C 100◦C and 130◦C.

It can be observed that the maximum power point for each ΔT is placed in the middle of the both curves P-V characteristic and P-I characteristic i.e V_{LMPP} = Voc/2 andV_{LMPP}= $I_{sc}/2$.

In practical TEG systems, the temperature difference applied to the TEG changes during operation. Therefore, the electrical operating point of the load needs to be updated frequently to maximize the power drawn in any heat changes. On the other hand, due to the imbalance of ΔT applied on the TEG surfaces, the internal resistance value changes for each temperature difference value and a different maximum power point (MPP) occurs in the P-V and P-I characteristics[12].

In order to achieve this load match R_{int} = R_L, a power converter controlled by the MPPT algorithm is required between the load and the TEG array. This MPPT algorithm enables the system to be operated in the maximum power poimt under various ΔT values.

IV. MAXIMUM POWER POINT TRACKING

A. Incremental Conductance Algorithm

Generally, DC-DC converters controlled by MPPT algorithm used to connect TEGs to storage elements such as batteries or supercapacitors. If the load requires a constant voltage for proper operation, another DC-DC converter can be used to feed the load from the battery with a constant regulated output voltage[13].
incremental conductance (INC) method is widely used due to its ease of implementation but has different issues such as confusion MPP release and rapidly changing of ΔT.
The incremental conductivity monitoring approach uses a fixed iteration step size.If the TEG characteristic has an operating voltage (V_{OP}) less than / greater than (V_{OP}), the slope of the power curve at this point will be positive / negative.
In fact, the algorithm is not expected to grab and operate the system in exact MPP. Therefore, practical INC algorithms are considered to have reached the MPP when the working point is within a certain margin of error.

$$\left|I + V\frac{\Delta I}{\Delta V}\right| < e$$

The MPPT efficiency of the InC algorithms is influenced by the noise in the circuit as well as the calculation of the correct results of the TEG output power.

In this study, a solution using Kalman filter is proposed to obtain a more accurate measurement. As discussed in [4] and [14], increasing the switching step results in high steady-state oscillation around the MPP reduces TEG power generation. On the other hand, increasing the accuracy of the measurements increases the complexity and power consumption of the MPPT control unit. This operational feature is particularly important in low power TEG applications.

The output power must be readjusted to eliminate noise effects on the INC methods, and a feedback control should be applied for the readjustment.Kalman Filter is the optimal linear

May – June 2020
ISSN: 0193-4120 Page No. 2156 - 2162

estimator provides data to the offset noise in the system. To overcome noise and changes in operating conditions, the filter simultaneously predicts the power state and provides feedback accordingly. The readjustment process is classified into two stages. The first stage relates to the measurement update represented in the predictive equations, the second stage refers to the time update processes represented in the corrective equations.

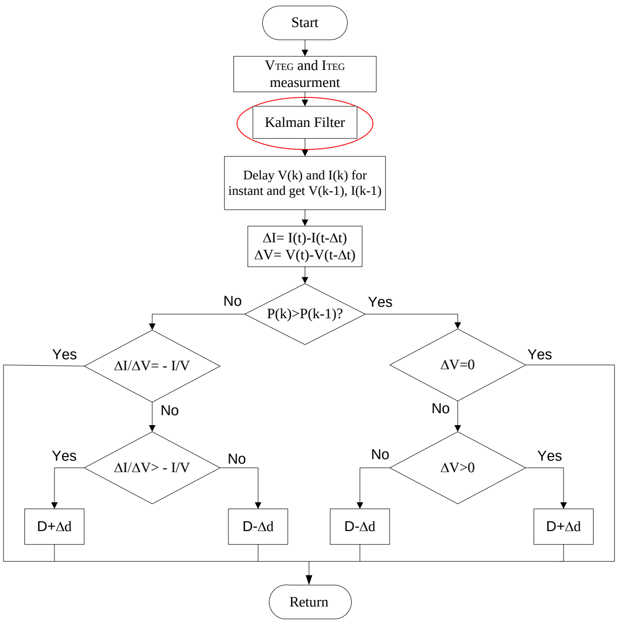


Figure 7. Flow Chart of enhanced INC Algorithm

V. Experiment and Results

In this section, an enhanced INC MPPT algorithm for harvesting energy systems is implemented and the results of the experimental studies are presented. The scheme of the TEHS system experimental as shown in the Fig. 7.

The system consists of TEGs, resistive load, Boostconverter, voltage sensor, a high sensitivity INA250 used as a current sensor,microcontroller (STM32F429) where kalman filter and INC MPPT algorithm is implemented.

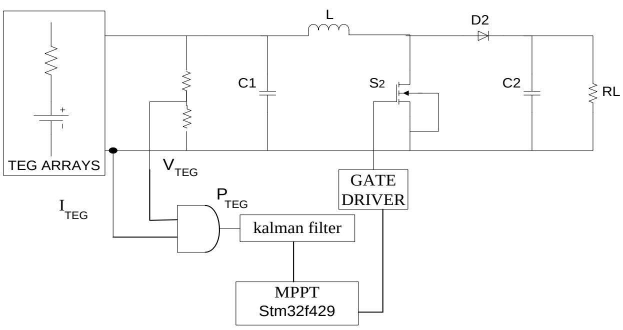


Figure 8. Schematic diagram of the proposed TEHS

Figure 9 illustratethe test platform which allows for real measurementsunder temperature difference across the terminals of the array with various resistance loads.

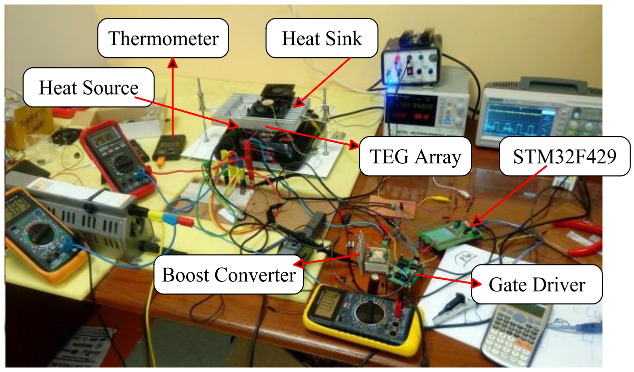


Figure 9. Energy harvesting prototype

In order to examine the efficiency of the modified INC algorithm under steady state condition, three different temperature differences ΔT, 80◦C, 100◦C, 130◦C were applied to the TEG array connected to the proposed system. Therefore, the efficiency is calculated according to the output power characteristics of the TEG and the output power of the MPPT converter at the optimum point for each ΔT.

This study adapted the INC MPPT algorithm which enhanced by applying a Kalman filter to control the boost converter. By sensing the output current and voltage of the TEGs array Kalman filter updates the measurements through three main processes the recursive measurement update process, the time updates process, and the fixing estimation process. the estimated values are used by INC algorithm to clarify the movement direction of the operation point as follow:

$$\frac{dP}{dV} = 0 \text{ For } V_L = V_{MPP}$$

$$\frac{dP}{dV} > 0 \; For \; V_L < V_{MPP}$$

$$\frac{dP}{dV} < 0 \; For \; V_L > V_{MPP}$$

These equations indicate that by increase/decrease the duty cycle of the boost converter the maximum power point is achieved at the time when the incremental conductance is equal to the negative of the instantaneous conductance. Fig. 10 shows the output current and voltage of the propsed approach.

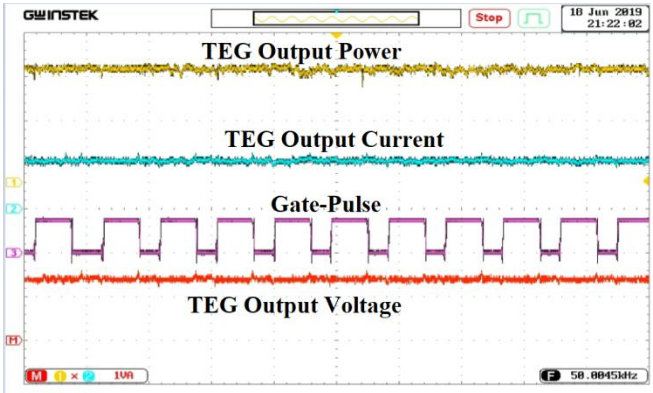


Figure 10. The Gate Driver Pulse Output Power, Current, and Voltage of TEG with STM32F429 Microcontroller

The Kalman filter is applied through a microcontroller for the measured voltage and current. Kalmanfilter successfully estimated and set/updated an optimal value for the sensed current and voltage and overcame the noises which appeared due to instability and rapidly of ΔT changes. Furthermore, this estimation ensures that the algorithm runs without any confusion. As shown in Fig. 11 the proposed technique shows higher efficiency than the stander INC algorithm.

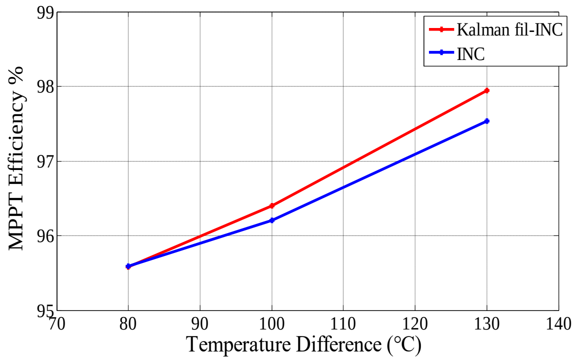


Figure 11. MPPT Efficiency vs Temperature Difference (80◦C 100◦C and 130◦C)

VI. CONCLUSION

This work suggested an algorithm to enhance tracking the optimum power under steady state and dynamic state for efficient MPPT. By using a Kalman filter which readjusts the characteristic of the thermoelectric generator. The influence of Kalman filter on the energy harvesting system was experimentally investigated. Moreover, The efficiency of the enhanced incremental conductance algorithm was compared to the conventional incremental conductance algorithm under various temperature difference. To confirm the validity of controlling the boost converter, by sensing the output current and voltage of the TEGs array, Kalman filter updates the measurements to to clarify the movement direction of the operation in INC algorithm . Finally, The experimental results proved that Kalman filter succeeded to estimated and set/updated an optimal value for the sensed current and voltage, this estimation grantee that the algorithm able to run without any confusion.

REFERENCES

[1] Reitz RD. Reciprocating internal combustion engines. Engine research center. University of Wisconsin-Madison; 2012 Princeton-CEFRC..

[2] W. Xie, G. Huang, X. Zhang and F. Deng, "A maximum power point tracking controller for thermoelectric generators," 2017 36th Chinese Control Conference (CCC), Dalian, 2017, pp. 9079-9084.doi: 10.23919/ChiCC.2017.8028802

[3] A. Belkaid, I. Colak and K. Kayisli, "Modeling and simulation of thermo electrical generator with MPPT," 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), San Diego, CA, 2017, pp. 855-860.doi: 10.1109/ICRERA.2017.8191181

[4] K. Yahya, M. Z. Bilgin, T. Erfidan and B. Çakir, "Improving the performance of the MPPT for thermoelectric generator system by using Kalman filter," 2018 5th International Conference on Electrical and Electronic Engineering (ICEEE), Istanbul, 2018, pp. 129-132.doi: 10.1109/ICEEE2.2018.8391315

[5] Phillip, N., Maganga, O., Burnham, K., Ellis, M., Robinson, S., Dunn, J., & Rouaud, C. (2013). Investigation of Maximum Power Point Tracking for Thermoelectric Generators. Journal Of Electronic Materials, 42(7), 1900-1906. doi: 10.1007/s11664-012-2460-4

[6] 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.

[7] Z. M. Dalala and Z. U. Zahid, "New MPPT algorithm based on indirect open circuit voltage and short circuit current detection for thermoelectric generators," 2015 IEEE Energy Conversion Congress and Exposition (ECCE), Montreal, QC, 2015, pp. 1062-1067.doi: 10.1109/ECCE.2015.7309806

[8] Z. M. Dalala and Z. U. Zahid, "New MPPT algorithm based on indirect open circuit voltage and short circuit current detection for thermoelectric generators," 2015 IEEE Energy Conversion Congress and Exposition (ECCE), Montreal, QC, 2015, pp. 1062-1067.doi: 10.1109/ECCE.2015.7309806

[9] I. Laird, H. Lovatt, N. Savvides, D. Lu and V. G. Agelidis, "Comparative study of maximum power point tracking algorithms for thermoelectric generators," 2008 Australasian Universities Power Engineering Conference, Sydney, NSW, 2008, pp. 1-6.

[10] 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, 2016, pp. 1-8.doi: 10.1109/ICCPCT.2016.7530195

[11] M. Elzalik, H. Rezk, E. G. Shehata, J. Thomas and R. Mostafa, "Thermoelectric Power Generation System-Simulation and Experimental Investigation," 2018 Twentieth International Middle East Power Systems Conference (MEPCON), Cairo, Egypt, 2018, pp. 298-303.doi: 10.1109/MEPCON.2018.8635251

[12] 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.

[13] Montecucco A, Knox A. Maximum Power Point Tracking Converter Based on the Open-Circuit Voltage Method for Thermoelectric Generators. IEEE Transactions on Power Electronics., 2015, 30(2), 828-839. doi:10.1109/tpel.2014.2313294.

[14] Mamur H, Ahiska R. Application of a DC–DC boost converter with maximum power point tracking for low power thermoelectric generators. *Energy Convers Manage*., 2015, 97, 265-272. doi:10.1016/j.enconman.2015.03.068.