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# Review of Heat Recovery Applications of Thermoelectric Generators

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**ABSTRACT**

Energy demand and environmental pollution are the hot topics of world summit discussions today. These two are directly proportional to each other and both have been increasing at an alarming rate in this technology-oriented world. In the past, energy production was increased to meet the demands but the recent energy crisis due to over usage of non-renewable sources has made us look into various options to increase the energy efficiency of systems. Co-generation has also been an area of interest for achieving energy efficiency. One of the small but promising field of increasing energy efficiency is waste heat recovery from all possible systems. Even though there are several methods of heat recovery, conversion of heat to electricity is the most popular one due to present power demand. Thermoelectric generators (TEGs) are one of the best possible solutions for this as they convert temperature difference directly into electricity. They are popular due to their compactness, solid-state structure and adaptability to any size of environment. Even though their efficiency is less researches are going on in this field and future of thermoelectric generators look very promising. This paper presents a review on the applications of thermoelectric generators and its power conditioning circuits for various applications.

**Keywords— thermoelectric generator, Seebeck effect, Dc-Dc converters.**

## I. INTRODUCTION

ways that have negative effects on human health and the environment due to their adverse effects on global warming and atmospheric pollution. Additionally, the consumption of liquid fuels in the world has increased from 91 million barrels per day in 2020 to 100 million in 2022 (U.S. Energy Information Administration,2020). The increase in demand has obviously accelerated the fuel cost. This has given a much-needed push to the search for sources of ‘green’ energy. This search has led us to look for small and decentralized sources of energy. Thermal energy is one such localized energy which is produced during industrial operations as well as our day-to-day activities. It has only been concentrated till now on the recovery and use of wasted heat in industries. Technological advancement has now made it possible to harvest even the smallest source of energy in an efficient way. Thermoelectricity is one such technology in waste heat recovery which aims at converting heat energy directly into electricity. The main factor which was hindering the wide spread usage of Thermoelectric Generators was its less efficiency. The integration of nanotechnology in the extraction of renewable energy source is a promising solution for this problem[45].

The real and complete success in the usage of the decentralized small energy sources is not only restricted to the efficient extraction methods but also in transferring the extracted energy to the load efficiently. Power conditioning circuits ensure maximum transfer of power from the source to the load. Thermoelectric generators are characterized by a lower voltage and a relatively high current(46). Their power conditioning circuits consist of DC-DC converters and controllers to adjust the duty cycle of converters. Converters which are capable of handling low voltage are required to make the output of TEG suitable for practical applications. In order to extract maximum power from the TEG they have to be made to work near full capacity. Intelligent controllers are used to continuously match the maximum power operating point of the TEG to the duty cycle of the converter to bring out the extracted energy efficiently. The fact that the devices in the power conditioning circuits also need energy for their operation has to considered while designing converters for low output applications. This paper reviews the heat recovery applications of TEG from various sources, the various configurations of converters and their algorithm-based controllers used in those applications.

The paper is organized as follows: Section I presents the applications of TEGs in various domains for heat recovery. Section II describes the various configurations of Converters used in these applications. Section III deals with maximum power point tracking algorithms used in the converters specifically for thermoelectric generators.

## II. APPLICATIONS

Renewable energy, especially solar energy has seen an incredible growth in the past few decades. It has immense potential in terms of photovoltaic and thermal energy. Till now both of them have been tapped separately as in co-generation. [1] implemented a Concentrated solar thermoelectric generator (CSTEG) to trap the heat of sunlight and

convert into electricity. Concentrated sunlight is made to fall on the hot side of the TEG to maintain high temperature and cold side heat is absorbed using heat sink. The arrangement is shown in Fig.1. Efficiency of 9.6% peak has been observed using this technology. Several modifications were made to CSTEGs to improve their performance like thermal and electrical optimization of the bismuth telluride based module[47],tapering the leg of the TEG module as shown in Fig.2 [48], [has beenIn this paper, solar thermoelectric generators are used in this process to produce the electricity by solar thermal power. Hot side of the thermoelectric generators are placed under the PV modules, and a cooling system was installed on the cold side of the thermoelectric generators with heat sink [1]
Experiment is integrated with twelve thermoelectric generators in a sedan-type hybrid electric vehicle for waste-heat recovery, it will recover the waste heat produced by the hybrid electric vehicle and convert it into electric energy, and stored it in a battery. They got the maximum power

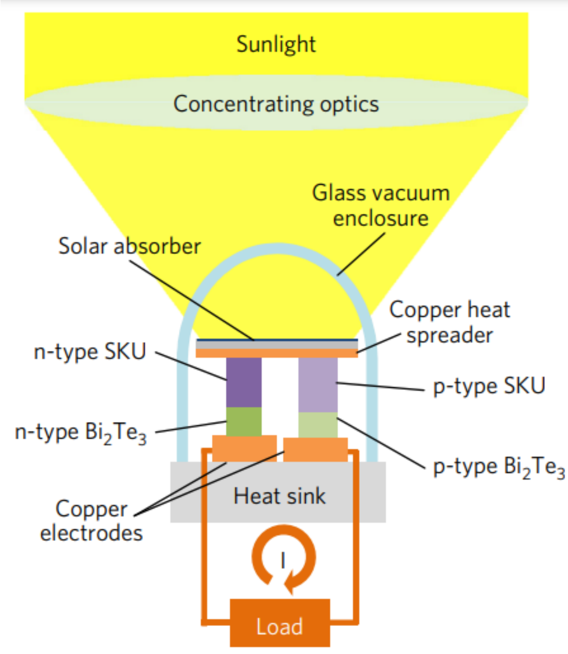


**Fig.1. CSTEG based on a pair of segmented p/n-type thermoelectric (TE) legs**

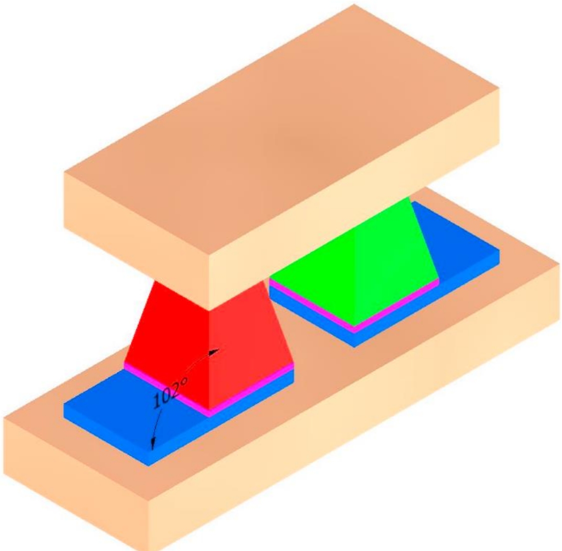


**Fig.2 output of 118W and an energy conversion efficiency of 2.1%. [2]**

In this experiment, thermoelectric generators are producing electric power by geothermal energy to produce hydrogen. Thermoelectric module (TEC1-12706) is used in this system. The electrical energy produced by thermoelectric generators will produces hydrogen by water electrolysis process to produce renewable hydrogen. The studies were conducted in a simulated model. [3]

a comparison of three types of thermoelectric generators that commercially available in the market with wood-fired stove was proposed in this paper. The system consists of Regulator, Thermoelectric generator, battery charge controller, battery and regulator. The first one is based on the air cooling type with the output of 45W, second one is based on the water cooling type with the output power of 100W, and the third one is also water cooling type with the output power of 350W. [4]

In this paper, solar thermoelectric generator system is used for long range wireless sensor networks for agricultural application systems. The CP60333 Thermoelectric module is used in this system attached with the heat sink, the hot side of the thermoelectric generator is recover the solar thermal energy, and the cold side the they maintained the environmental level temperature and achieving an open circuit voltage of 20-200mV from an single thermoelectric generator. [5]

In this paper, a household window frame customized to integrate 12 thermoelectric generators (TEG- 12715), and it is used to capture the sunlight falling on the window. The energy generated from that is stored in a power bank through a boost converter. The temperature difference is obtained by the hot sun outside and the air conditioning inside the room output. The researchers experimented for three days and didn't recorded any actual time to fully charge the power bank. [6]

In this paper, a combined thermoelectric generator (TEG), heat pipe, and heat sink system is presented for high efficiency Proton Exchange Membrane (PEM) fuel cells with ultra-low waste heat temperatures. Thermoelectric generator is placed on the mini hydrogen fuel cell. At 37◦C of waste heat temperature, they obtained the output value of 25.7mV and 218mW. [7]

In this paper, they recovered the heat energy from the body heat harvesting method by using the thermoelectric generators to generate electricity. The flexible TEG consists of 40 thermoelectric legs and the generated electricity was stored in the flexible Lithium-Sulphur (Li-S) battery. [8]

In this paper, thermoelectric generator is equipped on the cook stove, to recover the heat energy to produce electricity to run a fan. Thermoelectric generator is connected with the Luo converter to boost the output voltage. They obtained the output voltage of 12V for an input of 6V. [9]

The research is about the optimization of the electrical supply in the off-grid systems including thermoelectric generator, wind, and photovoltaic cell. The hot side of the thermoelectric generator is placed on the cook stove exhaust. They used Maximum Power Point Tracking [MPPT] controller and Dc/Dc converter to increase the output power to store it in the battery. [10]

In this paper, the thermoelectric generators are combined with Liquefied Natural Gas production process to recover the heat energy into electric energy. The thermoelectric generators are placed in two different locations in the LNG cycle, in case 1 they placed TEGs between condenser and evaporator, and in case 2 they placed it between condenser and ambient, and they stored the recovered electrical energy in the battery. [11]

In this paper, thermoelectric generator was applied to the liquid air energy storage system to utilize the excess heat. The hot water outlet temperature of 60-80◦C was placed on the hot side and on the cold side the air turbine is placed to generate the electricity. [12]

Experiment is conducted in Water pH monitoring sensor which powered by thermoelectric generator with the Phase-Change Material (PCM). The thermoelectric generator is placed in the bottom of the housing with heat sink for the hot side of the TEG and the cooler side is emerged with water pipe attached with heat sink. The energy harvested from the TEGs was stored in the thermal battery. [13]

Flexible thermoelectric generators are integrated with wearable devices for producing its own electric power through body heat harvesting. Due to the advantages of thermoelectric generators, like non-moving, without sound, it can be used in medical applications. [14]

In this paper, thermoelectric generators and chaos-shaped brass heat exchanger is constructed to power the Military sports utility vehicle (SUV). An automobile exhaust thermoelectric generator (AETEG) is assembled into a prototype military SUV. It uses four TEGs connected thermally in parallel and electrically in series, and obtained a maximum output power of AETEG is 646.26 W, and conversion efficiency is 1.03%. [15]

In this paper, series of six thermoelectric generators are placed in the automobile two stroke engines, to recover the waste heat energy produced in the vehicle exhaust. The hot side of the thermoelectric generators will observe the waste heat energy of a vehicle, and cool side of the thermoelectric generator is cooled with air coolant, and the energy produced will be stored in the battery. [16]

## III. DC-DC CONVERTERS USED IN THERMOELECTRIC GENERATORS

To boost the voltage output of the thermoelectric generators Cuk converter is proposed in this experiment. Cuk converter is the combination of buck and boost converter, which produces the stable and maximum output from the TEGs [16]

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In this paper, thermoelectric generator harvesting method with body heat is proposed with a colpitts oscillator-based dc-dc boost converter. They achieved 40mV with an enhanced swing colpitts oscillators with 10 stage voltage multiplier with an efficiency of 75%. [17]

In this paper, thermoelectric generators power output value is boosted with Dual-Stage boost converter for ultra-low power applications. This converter supports the self-startup by using a transformer-based oscillating mode. The converter achieves the energy harvesting efficiency of 81.5%. [18]

In this paper, thermoelectric generators is proposed with an single-inductor boost and buck-boost hybrid converter with a reversal in polarity. The converter proposed in this system is implemented in a 0.13-μm CMOS process. The converter achieves over 70% end to end efficiency and a peak efficiency of 91.5% and for the available power ranging from 4.3 μW to 429 μW. [19]

In this paper, thermoelectric generators are placed in the vehicle exhaust to recover the waste heat energy into electric energy. The output of the thermoelectric generator is stabilized with the help of Cuk converter and it increased the efficiency of thermoelectric generator also. The energy produced in the system was stored in the system. [20]

The performance of dc-dc converter connected with thermoelectric generator is analyzed is this experiment. The efficiency of the converter is ranges between 78.52% - 81%. The Dc-Dc converter increased the efficiency of the thermoelectric generator and stabilized the output voltage. [21]

The author presented consists a new method for detecting and reversing the polarity of a low-voltage thermoelectric generator (T.E.G.) in inductor-based converters. The converter uses the inductor response to a voltage change in response to the flipping of the T.E.G. polarity. The authors found that their proposed auto-polarity method has a peak efficiency of 70%. [22]

The proposed system contains 280 thermocouples, electrically connected as the parallel of two blocks, each of which contains 140 thermocouples. In order to step up the voltage at the output of the thermoelectric generator, a DC-DC converter has been designed. The proposed DC-DC converter achieves an automatic control based on pulse width modulation (P.W.M.) and is implemented in CMOS technology. The author found that the proposed converter achieved 73% peak efficiency. [23]

A dc–dc boost converter with the variation-tolerant M.P.P.T. technique and a high-efficient Z.C.S. control circuit for thermal energy harvesting has been proposed in this paper. The M.P.P.T. scheme dynamically controls the switching frequency and extracts the maximum power from the T.E.G. The converter was implemented in a B.C.D.M.O.S. process and they founded that the converter had a peak efficiency of 72%. [24]

The authors presented a new M.P.P.T. algorithm and a DC-DC converter to extract maximum power from a thermoelectric generator. They compared their new M.P.P.T. algorithm and Perturb and Observe (P&O) algorithm. Their simulation and test results show that their proposed algorithm has superior performance as compared to that of the Perturb and Observe (P&O) algorithm. [25]

The author proposed a single-inductor, dual-input, dual-output (S.I.D.O.) dc-dc converter with double-mode capability and matrix-capacitor array (P.C.A.) maximum power point tracking (M.P.P.T.) control for thermoelectric energy harvesting. The converter was implemented within a CMOS processor, and the peak power conversion efficiency of this converter was found to be 84.6%. Their PCA-MPPT-controller achieved a tracking efficiency of 99.55% without changing the switching frequency. [26]

Theoretical analysis of DC-DC Flyback converter in energy harvesting based on thermoelectric generator is proposed in this paper. The converted is integrated with MOSFET IRF540N model and U1520 diode model. A circuit was simulated in spice and implemented in an 18W prototype and their experimental results showed that the converter has an efficiency of 96.5%. [27]

## IV. CONTROLLERS USED IN THERMOELECTRIC GENERATOR APPLICATIONS

The authors proposed a boost converter with ultralow-voltage time-domain control for thermoelectric generators (T.E.G.s). The maximum power point tracking (M.P.P.T.) is realized by using the fractional open-circuit voltage scheme. Their proposed converter is implemented in a 0.13-μm CMOS process. They analyzed the proposed boost converter in two power stages. They are i) fractional open-circuit voltage (F.O.C.V.) sampling and ii) voltage conversion using a boost converter, and they found that the peak M.P.P.T. efficiency is 95.1%. The boost converter has the highest conversion efficiency 76.92%. [28]

The author proposed a step-up switching converter system that tracks the impedance matching changes that deliver the maximum power by Maximum Power Point Tracking (M.P.P.T.) method to take the maximum efficiency from thermoelectric generators. The proposed prototype was fabricated in 0.5 μm CMOS where efficiency measurements showed a maximum peak efficiency of 61.15%. [29]

The author proposed an innovative way to measure the open-circuit voltage during a pseudo-normal operation of a power electronic converter. Using M.P.P.T., buck-boost converters are controlled synchronously using theoretical analysis. The prototype M.P.P.T. converter is controlled by a microcontroller, and the lead-acid battery stores harvested energy. Tests with commercial T.E.G. devices showed that the converter tracked the maximum power point with an accuracy of 99.85%. [30]

In this paper, the author proposed a thermoelectric energy harvesting system based on a Boost converter with four different maximum power point tracking (M.P.P.T.) algorithms that store energy in a super capacitor. Perturb and Observe (P&O), Incremental Conductance (I.N.C.), Open Circuit Voltage (O.C.V.), and Short Circuit Current (S.C.C.) algorithms were tested to improve the designed circuit. Their experimental results show that the O.C.V. algorithm resulted in being the fastest to charge the super capacitor. [31]

In this paper, a Step-Up DC/DC converter and Maximum power point algorithm are used to track the gain of the maximum power output from the thermoelectric generator. Their proposed converter was designed and built for operation with a (TEP1-12656) T.E.G. The authors implemented fractional short-circuit M.P.P.T. algorithm and P&O in the converter and they found that the fractional short-circuit M.P.P.T. algorithm produced a more stable output over the operation range. [32]

In this paper, al fully autonomous interface circuit for energy harvesting from T.E. modules is introduced, where the circuit consists of a self-starting DC-DC converter based on a dual-phase charge pump with LC tank oscillator, a digital M.P.P.T. unit, and a 1-V LDO regulator. The M.P.P.T. controller tracks the maximum power point and changes the duty cycle of the converter. The author founded that the M.P.P.T. controller achieved the peak efficiency of 98%. [33]

In this proposed system, the author generated the electric power from the thermoelectric generators and hybrid photovoltaic cells. To increase the output power DC-DC converter and Lock-On Mechanism (L.O.M.) algorithm is used to achieve M.P.P.T. for the hybrid photovoltaic cell and thermoelectric generator (PV/TEG) system where this algorithm is applied to a double SEPIC converter. The double SEPIC converter is composed of two single SEPIC converters whose output capacitors are connected together in parallel, and they observed that dc-dc converter with M.P.P.T. based model is able to effectively extract the maximum power. [34]

An energy harvesting device with dual inputs for combining heterogeneous sources of energy was proposed, fabricated, and successfully tested by the author. The input energy sources are from an electromagnetic vibration energy generator (E.V.G.) and a thermoelectric energy generator (T.E.G.). They proposed a current boost converter and M.P.P.T. algorithm for this system. They found that their proposed system has an end-to-end peak efficiency of 82% and an average of 75% efficiency. [35]

In this paper, thermoelectric generators are connected with the maximum power point tracking (MPPT) and time exponential rate perturbation and observation (P&O) to get maximum power output from the thermoelectric generator (TEG). The MPPT circuit was implemented in a 110 nm complementary metal-oxide semiconductor (CMOS) process. The tracking efficiency maintained a high level from 98.9 to 99.5%. The applicable range of the TEG resistance was from 1 to 12 Ω, which reflects an enhancement of at least 2.2 times. [36]

Thermoelectric modules are installed are installed with Automotive thermoelectric generator (ATEG) which produces electrical power by recovering the waste heat energy of engine exhaust gasses. Maximum power point tracking (MPPT) method is used. It will track the maximum power point produced by the converter and change the duty cycle of the converter to get the maximum output. The experiment is conducted with the simulation of buck boost converter with the perturb and observe (P&O) algorithm with a modification of the duty cycle. [37]

An integrated thermoelectric power generation system is discussed here that involves a non-isolated high-step-up DC-DC converter with switched capacitor cells which provides the high voltage gain. TEG maximum power points are tracked using the Perturb and Observe (P&O) technique using Maximum Power Point Tracking (MPPT). An efficiency of 87.51 has been achieved by the proposed converter with TEG. [38]

A soft-switched isolated step-up DC–DC converter designed to harvest thermoelectric energy. This converter utilizes the MPPT algorithm to enhance its overall efficiency. The algorithm will track the maximum power point value produced by the TEG and change the duty cycle of the DC-Dc converter based on the Maximum power point value The efficiency of conversion from the Thermoelectric source is about 92%. Perturb and Observe (P&O), Incremental Conductance (INC), and Modified Incremental Conductance (MINC) tracking techniques are employed in this study to determine the maximum power.[39]

PV/TEG hybrid system combines solar panels with thermoelectric generators. A double-input boost converter creates the combined energy needed to supply the DC load. A hybrid system has been implemented using MPPT based on SM algorithms to maximize the generated power. The algorithm will track the maximum power point value produced by the TEG and change the duty cycle of the DC-Dc converter based on the Maximum power point value. [40]

A steady state thermoelectric generator module with 199 pairs of couples was proposed in this system. The algorithm will track the maximum power point value produced by the TEG and change the duty cycle of the DC-Dc converter based on the Maximum power point value. The output power of the thermoelectric generator is optimized with mutation particle swarm optimization (M-PSO). Optimal output power and efficiency were obtained when temperature differences were below 40 K (19.6 W and 4.05%, respectively). [41]

204 thermoelectric generators are connected in the series with DC-DC boost converter to convert the heat energy into electrical energy. The maximum power point tracking (MPPT) algorithm was proposed in this system. The algorithm will track the maximum power point value produced by the TEG and change the duty cycle of the DC-Dc converter based on

the Maximum power point value. The TEG module is modelled and the whole system is simulated successfully using MATLAB SIMULINK R2017a. IT2FLC MPPT technique is made and simulated for a TEG module. [42]
2017
Thermoelectric generator is integrated with automobile exhaust to produce electric power. A hybrid maximum power point tracking method combining perturb and observe (P&O) algorithm is used in this system to get the maximum output power from the TEG. The algorithm will track the maximum power point value produced by the TEG and change the duty cycle of the DC-Dc converter based on the Maximum power point value in the experiments, a buck DC/DC converter was developed and applied based on MATLAB/Simulink models and simulations of the AETEG system. Both the simulations and experiments validate the hybrid MPPT algorithm as feasible and efficient. [43]

## V. CONCLUSION

In this paper, we presented an in-depth analysis of thermoelectric generators for the recovery of thermal energy in various sectors using different DC-DC converters, and various algorithms.

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