ISSN (Online) 2393-8021
ISSN (Print) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology
Vol. 2, Issue 9, September 2015

Fractional Open Ciruit Voltage Controlled Converter Based Thermoelectric Generator

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Abstract: The thermoelectric generator (TEG) is thepredominant compact, solid-state heat engine. Effectiveutilization of a heat resource using a TEG requires maximizing its power output by interposing a regulated power converter between the source and load. It is criticalto track the optimum electrical operating point through the useof power electronic converters controlled by a maximum power point tracking (MPPT) algorithm. MPPT algorithm used here is the open circuit voltage method. Using an efficient buck boost converter the power output of TEG is fed to a battery.

Keywords: Thermoelectric Generator (TEG), Maximum Power Point Tracking (MPPT), Perturb and Observe Method (P & O).

I. INTRODUCTION

Thermoelectric module (TEM) [3] is a solid-stateenergy converter which converts waste heat into electricity. Normally it consists of an array of2Npellets from p and n type semiconductor material that make up Nthermoelectric couples. They are joined thermally in parallel and electrically in series. The TEM can be used for cooling, heating, and energy generation. As a thermoelectric cooler (TEC), the TEM has found applications in thermal management and control of microelectronic devices such as diode lasers and CPUs. As a thermoelectric generator (TEG), the TEM could be used to produce electric power in remote locations when temperature gradients are available.

Due to relatively high cost and low efficiency the use of TEGs has been restricted in the fields such as in medical, military, remote, and space applications. However in recent years, due to the increasing environmental issues and energy cost have motivated research into alternative commercial methods of generating electrical power.

Thermoelectric generators can be applied in a variety of applications. Frequently, thermoelectric generators are used for low power remote applications or where bulkier but more efficient heat engines such as Stirling engines would not be possible. Unlike heat engines, the solid state electrical components typically used to perform thermal to electric energy conversion have no moving parts. The thermal to electric energy conversion can be performed using components that require no maintenance, have inherently high reliability, and can be used to construct generators with long service free lifetimes. This makes thermoelectric generators well suited for equipment with low to modest power needs in remote uninhabited or inaccessible locations such as mountaintops, the vacuum of space, or the deep ocean.

Despite all advances in the miniaturization of Microsystems which depend on a central power source or bulky batteries with limited lifetime. Growing fields like autonomous Microsystems or wearable electronics urgently look for micro scale power generators. One of the effective solutions is to convert waste heat into electrical power with TEG [1].

Thermoelectric generator is one of the most useful and environment friendly device with the advent of semiconductor materials the efficiency of a TEG can even be an alternative for the conventional heat engines [7].

The magnitude of the TEG's open-circuit voltage is directly proportional to the temperature difference, as specified in seebeck effect. TEGs can be connected in series or parallel in order to achieve desired levels of voltage and current. In order to interface TEG to the load power electronic converters such as buck, boost or buck-boost converters are commonly used. The selection of converter topology depends on the output and input voltages; for example, for connection to dc microgrids a high step-up gain converter is used, while for connection to a 12-V car battery a Buck or Buck–Boost type can be used. In this paper we are using a synchronous Buck-Boost [2], [7] to guarantee a wide input voltage range and consequently harvest power from the TEGs over a wide range of operating temperatures.

A. Principle of operation

Thermoelectric generators (also called Seebeck generators) are devices that convert heat (temperature differences) directly into electrical energy, using a phenomenon called the See beck effect (a form of thermoelectric effect).Five main physical processes take place in a TEM [3] such as Thermal convection, Seebeck power generation, peltier heating/cooling, Thompsonphenomenon. A thermoelectric produces electrical power from heat flow across atemperature gradient. As the heat flows from hot to cold, free charge carriers (electrons or holes) in the material arealso driven to the cold end as in fig. 1. The resulting voltage (V) is proportional to the temperature difference (ΔT) via the Seebeck coefficient, α, ($V = \alpha\Delta T$). As shown in fig.1, each voltage adds up as in series connection and when a load is connected to the TEG's terminals, current flows from hot side to cold side. This current flow produces heat by Joule heating and pumpsadditional heat from the hot to the cold side because of the Peltiereffect, which is an effective method in power generation. A high load current

DOI 10.17148/IARJSET.2015.2914

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International Advanced Research Journal in Science, Engineering and Technology
Vol. 2, Issue 9, September 2015

amplifies the Peltier effect, whichincreases the effective thermal conductivity of the device whichin turns decreases the temperature difference ΔT.

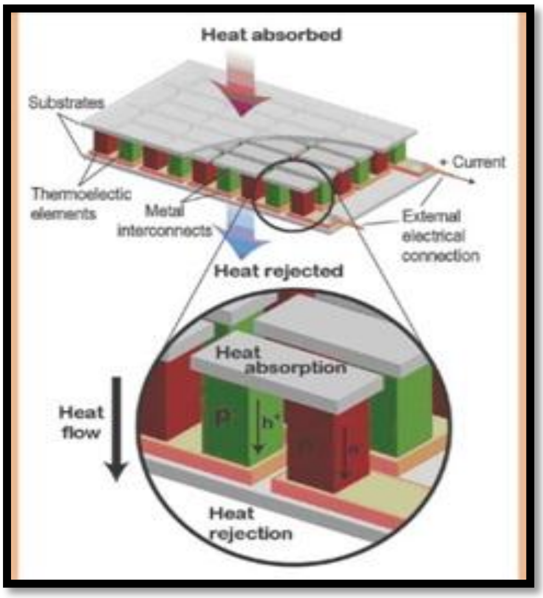

Fig.1. Schematic represesntation of thermoelectric generator

Thermoelectric generator will extract waste heat from the exhaust that will deliver DC electrical power to recharge the battery. By reducing or even eliminating the need for the alternator, the load on the engine is reduced thereby improving
fuel efficiency by as much as 10%.We can use the waste heat as heat source for a thermoelectric generator as shown in Fig. 2 which converts the waste heat directly into electric energy.The heat energy from the exhaust gas needs to be conducted to the TEM (hot side) by a heat exchanger and the TEM has to be cooled on the cold side. The electric power output has to be integrated into the electric network of the application and, for an optimum efficiency, it has to be controlled. The actual configuration of the systems strongly depends on the boundary conditions.

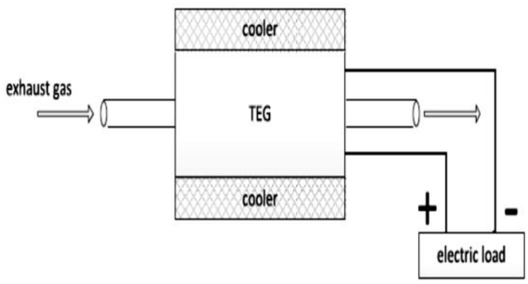

Fig.2. Waste heat usage with the hellp of thermoelectric generator

TEG can be designed as a dc source in series with an internal resistance. It is necessary to control the power electronic converters used to interface TEG to the load with a maximum power point tracking (MPPT) algorithm. The load can be a battery [5]. Care should be taken to match the virtual load seen by the TEG to its actual internal resistance by changing the duty cycle of the converter. The MPPT algorithm [4] used here is the fractional open circuit voltage method. In order to use this algorithm synchronous buck-boost converter is designed, which can be effectively used for low power applications. The load can be a lead acid battery which is supplied from the converter.

The maximum power point voltage has a linear dependency on the open circuit voltage V_{OC} under different irradiance and temperature conditions. Computing the MPP (Maximum Power Point) comes down to:

The output voltage of the converter can be designed with respect to the duty cycle and the input voltage.

When the converter is designed for a duty cycle of 0.5 the output voltage will be same as the input voltage. When the value of D < 0.5 buck operation takes place and when D >0.5 converter works in boost mode.

II. MPPT METHODUSED

The FractionalV_{OC}/I_{SC} method [6] uses the observation thatthe relationship between the MPP voltage/current and the open/short-circuit voltage/current for a PV module is approximately given by and respectively. The drawback of the method in PV system is that the value of k_1 and $k_2$varies from module to module and this should be defined prior to the algorithm. On the other hand the relationship is not linear and changing the value of k results in steady state error. As a result the FractionalV_{OC}/I_{SC}method is used less frequently with PV modules than the P&O or Incremental Conductance.
Plotting the V-I characteristicof a TEG reveals a linear characteristic that canbe modeled by a voltage source in series with a resistor. For this model the voltage source represents the opencircuitvoltage of the TEG, which is directly proportional tothe temperature difference applied to it, while the resistor issimply the electrical resistance of the TEG. The linear V-Icharacteristic results in a parabolic P-I characteristic withitsmaximum located at exactly half of the short circuit current.
This is equivalent to half of the open circuit voltage and thusk1 = k2= 0.5. Unlike PV modules this ratio does not changeregardless of operating conditions. It should be noted that theTEG resistance varies slightly with temperature however thisonly changes the gradient of the V-I characteristic and not itslinear nature.Therefore the advantage of this method over a hill-climbingalgorithm is the reduced oscillations in the control signal atsteady state.Changes in the load have no effect on the value of V_{OC} or I_{SC} and thus can be tracked withoutre-determination of the operation set point. Also, since theconverter only requires the measurement of one parameter, thetracking of load changes can be faster than hill-climbing thatrequires the measurement of two parameters. Changes in temperature willrequire the re-measurement of V_{OC} or I_{SC}in the MPPT method adopted here [4].

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III. CONVERTER SYSTEM

This section deals with the snubber circuit, synchronous buck boost converter used to interface TEG to the load. The entire system is shown in fig. 2. TEG can equivalently represented by an open circuit voltage V_{oc}, followed by the internal resistance of the device R_{int}. asnubber circuit is introduced before the buck-boost converter for suppressing the over-voltages.

A buck (step-down) converter combined with a boost (step-up) converter is termed as a buck boost converter. The output voltage is typically of the same polarity of the input, and can be lower or higher than the input. Such a non-inverting buck-boost converter may use a single inductor which is used for both the buck inductor and the boost inductor, sometimes called a "four-switch buck-boost converter.

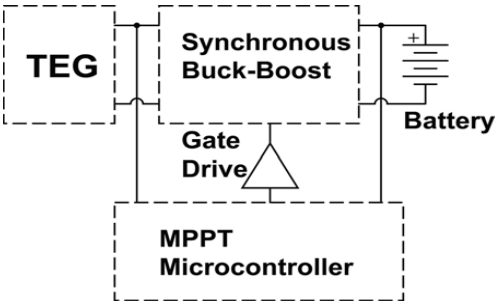

Fig.2. Block diagram of the complete system

A. Snubber Circuit

Snubber suppresses voltage transients in the electrical systems. Snubbers are frequently used in electrical systems with an inductive load where the sudden interruption of current flow leads to a sharp rise in voltage across the current switching device, in accordance with Faraday's law. By using the snubber circuit we can reduce the voltage and current spikes. Snubber circuit shapes the load line within safe operating area. The operation of snubber circuit includes power dissipation from the switch to a resistor or a useful load. It will also reduce switching losses along with the EMI by damping voltage and current ringing.

A rectifier diode is often used as a snubber when the current flow is DC.In order to measure the open circuit voltage TEG should be disconnected from the load. This results in oscillations having a frequency in the range of megahertz.

In the circuit of Fig. 3, when $M_{cap}$is closed and at the beginning of t_{off} , M_1 is opened, I_{in}finds an alternative path into C_{in}, which is a fairly big capacitance. This cannot happen when $M_{cap}$is open, hence the TEG is suddenly open-circuited. The current in $L_p$cannot stop flowing instantaneously and its energy is dissipated in the ringing with the parasitic capacitances of the circuit, damped by R_{int}, i.e., an RLC circuit. The decrease of I_{in}reverses the voltage across the parasitic inductance, so that a voltage considerably greater than V_{OC} appears at the converter's input.

The energy stored in the capacitor C_{in} is

From (3), it is possible to obtain V_{Cin}, which is thevoltage on C_{in}at the end of the V_{OC}measurement procedure. Also the parasitic inductance in the TEG can be calculated approximately from (4). The energy stored in the inductor $L_p$can be expressed as:

In order to damp the overvoltage, while still achieving a fast transient of the TEG's voltage to the open circuit, a capacitor $C_S$is added across the TEG's terminals. $C_S$needs to be sufficientlylarge so that the energy transferred from LP does not charge itto much more than V_{OC}, but small enough to let V_{TEG}quicklysettle to V_{OC}. The value of C_s can be calculated from equation (5) as

In snubber circuit when two diodes, $D_{S1}$and D_{S2}, are used to add some damping due to their conduction resistances, and to provide a Schmitt trigger function because of their voltage drops. The resulting circuit is effectively a diode capacitor diode (DCD) snubber, which suppresses overvoltages storing energy during $t_{off}$and releasing it back during t_{on}.

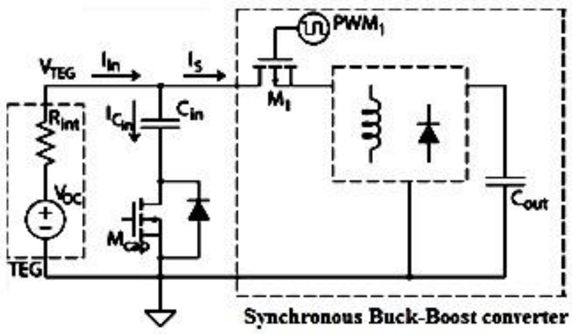

Fig.3. Complete schematic of the arrangement

B. Synchronous buck boost converter

A non-inverting buck-boost converter [9] is a cascadecombination of a buck converter followed by a boostconverter. For low voltage applications, the efficiency ofthe buck-boost converter is improved by replacing the rectifier diodes with switches, which results in a synchronous converter topology. The schematic representation of the converter [2] is shown on fig. 4. During the T_{on}period of the cycle, switches $M_1$and M_3 are ON and the input voltage is impressed across the inductor.Since the load current is instantaneously provided by the outputcapacitor during this interval, the capacitor voltage (outputvoltage) decreases. During the other interval of the switching period, switches $M_2$and M_4 are turned on and theinductor energy is transferred to the output, providing both theload current and also charging the output capacitor. There will a time delay or dead time between the turn off of M_1, M_3 and M_2, M_4. During this time the inductor current flows through the diodes D_1 and D_2 from M_2 and M_4 preventing over shoot current. The duty cycle of the converter is given as

Where T is the switching time period of the converter.

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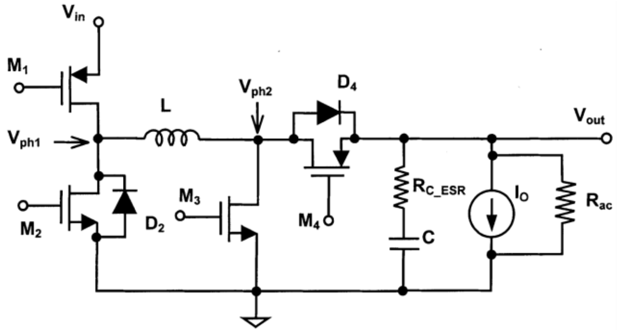

Fig.4. Synchronous buck boost converter

IV. SIMULATION RESULTS

Simulation of the entire system is developed in matlabsimulink. TEG is equivalently represented using a dc voltage source in series with internal resistance. A snubber circuit is connected after the TEG in order to prevent the overvoltage transients. The synchronous buck boost converter is designed for closed loop using the MPPT algorithm. The output of the converter is fed to a 12V lead acid battery. In matlabsimulink the output is taken across the resistive load.

Simulation model for the closed loop system is shown in fig. 5. The waveforms obtained for the open loop control are also plotted in fig. 6. The circuit is designed with input and output capacitors of 440μF and 660μF respectively. The inductance of the buck boost converter is designed as 0.8mH and thesnubber capacitance is 180μF. The system is delivering a rated power of 35W. Control of the switches is done using PWM technique in the open circuit method. While in the closed circuit method the open circuit voltage method will be using as the feedback system.

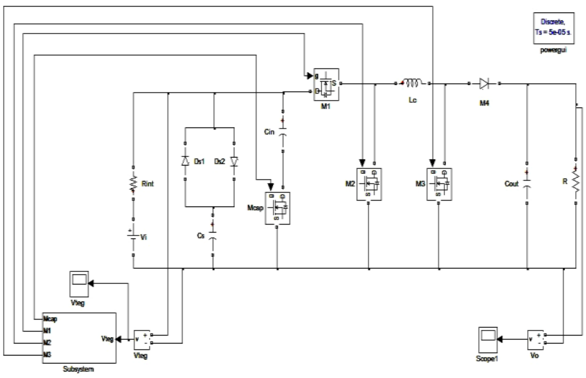

Fig. 5Matlab Simulink model of closed loop control

It is impossible to instantaneously change the open-circuit voltage; therefore the TEGs have been replaced by a power supply in series with a power resistor in the model. The circuit is designed for an input voltage of 12V and a duty cycle of 0.5. The output voltage and current corresponding to 12V open circuit voltage is shown in fig. 6.The closed loop control of the system is done using the MPPT algorithm. MPPT technique proceeds by measuring the TEGs voltage by disconnecting TEG from the circuit using the M_{cap}switch.

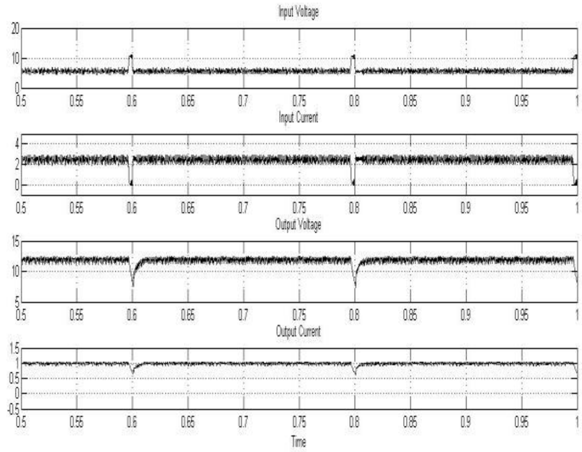

Fig.6. Waveforms of input voltage, output current, output voltage

In the hardware part the input to TEG is given using an iron box in the hot side and ice cubes in the cold side and obtained an output of 12V is used to charge a battery of 12V rating. TEG is stacked between heat sink using thermal paste. Two TEG's are connected in series to obtain an output of 12V. As in the application side we can connect TEG to the exhaust pipe of vehicles and can produce electricity proportional to the temperature in the output side of exhaust pipe. In the prototype we designed we are using the output of TEG to charge a lead acid battery of 12V.

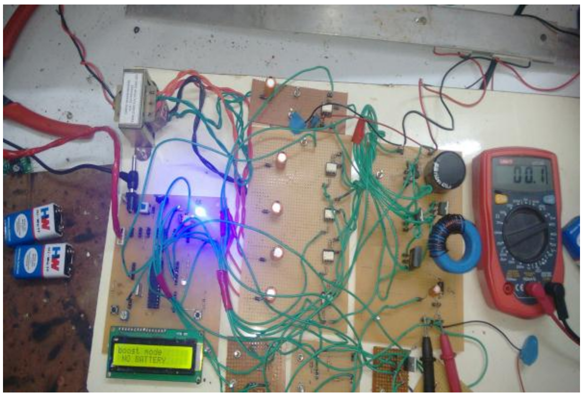

Fig.7. Experimental setup

In the modification part the battery is protected from overcharging and under charging by introducing a boost charging mode and battery full mode. If the input to the battery is less than 9V then the system will automatically switched to boost mode. If the battery is charged completely, ie, if battery voltage is greater than 13V then the battery voltage automatically drops down.

V. CONCLUSION

The paper presents an efficient way to harvest the waste heats which are ejected from engines and several other sources in our day today life. The MPPT algorithm is programmed to a low-cost microcontroller ATMEGA328p and does not require expensive sensors.

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International Advanced Research Journal in Science, Engineering and Technology
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A dc–dc non-inverting synchronous Buck-Boost converter is used, which can work in Boost, Buck-Boost or Buck mode; thereby harvesting power over a wide range of temperature differences across the TEG.
The circuit is modified with constant charging of battery thereby reducing the chances of draining out of battery or overcharging of battery.

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