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AN INNOVATION OF TRIGENERATION WITH THERMOELECTRIC MODULES

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Abstract – A Thermoelectric Cooler, or TEC as it is commonly known, is a small device consisting of many P-type and N-type semiconductor blocks that is used to create temperature difference between its sides. Typically the dc supply voltage to TEC is 12V. Since this principle is generally called as the Peltier effect, this device is also named as a Peltier module. It also shows the reverse effect called as the Seebeck effect. When a temperature difference is maintained across its plates, a voltage is generated across the terminals of the module. Thus, it may also be configured as a thermoelectric generator or TEG. This paper deals with an innovative idea on air cooler by exploiting the behaviour of a Peltier module. The basic principle deals with the conversion of heat energy directly to electrical energy using Peltier module so as to reduce the temperature in the surrounding region resulting in a cooling effect. The aim of this work is trigeneration involving TEC/TEG modules. Further use of Joule thief circuits and energy harvester circuits are also discussed to provide a future research scope in this topic.

Index terms -- Thermoelectric air cooler, Trigeneration, Heat Sink, Joule thief Circuit, Peltier Module, Energy harvesting.

I. INTRODUCTION

The main effect of global warming is the increase in the overall temperature of the environment that has led to a lot of harm to many of the living organisms. One of the methods that is used worldwide to get comfort in this drastic conditions is the use of air conditioners and air coolers that makes use of refrigerants or water to push out the heat from a closed room to the external surroundings, thereby creating a comfortable temperature inside the room. But, even these methods lead to the increase in the environmental temperature, thus contributing to global warming.

In this paper, the basic principles of the innovative way of air cooling is proposed, where the heat energy in a room is concentrated and is converted to electricity using thermoelectric generators resulting in a reduction in room temperature. This method of air cooling does not have any harmful effects on the environment as the heat from a closed room is not being pushed to the external surroundings of the room. Instead, the same heat in the room is converted to electrical energy that can be used for any other purposes such as lighting.

Trigeneration is the synonym of combined cooling, heating and electric power generation. The idea is to transfer the residual heat energy of the room to another part, and use that heat energy for generating electricity which can be used for lighting purposes. This process causes a cooling effect inside the room. Through this paper, we are also aiming on taking this idea to the next stage by making use of DC – DC booster circuits such as Joule thief circuit and energy harvester circuits using Linear ICs so as to make the generated electrical energy to a form that can be used in many of the domestic applications.

II. THERMOELECTIC PELTIER MODULE

Thermocouples are the basic elements of the thermoelectric device. Thermocouples are fabricated from P- and N-type semiconductor material that perform solid-state energy conversion. These devices have the capability of generating many microvolts per degree temperature difference, and can provide useful amounts of electrical power in selected applications. A thermoelectric module is made up of a number of thermocouples connected together electrically in series and thermally in parallel [4]. The Fig (i) shows the three dimensional view of the typical thermoelectric module. Thermoelectric modules are fabricated on ceramic plates that serve as a foundation and electrical insulation for two P- and N-type bismuth telluride (BiTe) thermo-elements. The BiTe thermo-elements are connected electrically in series and thermally in parallel between the ceramics plates. These modules usually contain between three and 127 thermocouple pairs and vary in size, power handling (1 –125 W) and maximum differential temperature (130°C between the hot and cold junctions). For our work we made use of a commercially produced 12706 TEC thermoelectric module shown in Fig (ii). A Thermoelectric power generator is a solid state device that provides direct energy conversion from thermal energy (heat) i.e, a temperature gradient into electrical energy based on "Seebeck effect" [1]. In fact, this phenomenon is applied to thermocouples that are extensively used for temperature measurements. Based on this Seebeck effect, thermoelectric devices can act as electrical power generators [6].

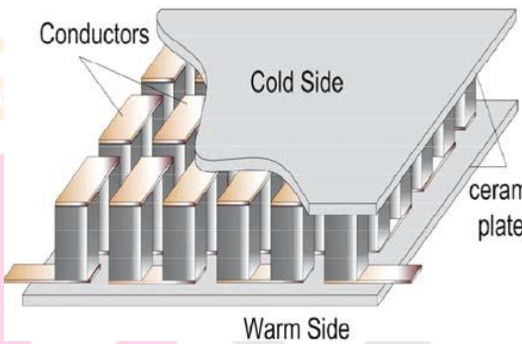

Fig (i): Thermoelectric Module(Picture courtesy: *Waste energy harvesting with a thermoelectric generator*, by ShaveenMaharaj and PoobalanGovender, Durban University of Technology)

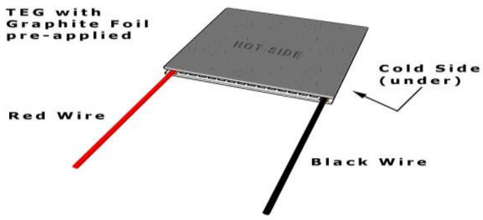

Fig (ii): TEC 12706
(©www.customthermoelectric.com/powergen/images/126-cpl-Power-Gen-40mm-R2-300C-graphite2.jpg)

Fig (iii) shows the module working as a thermoelectric generator. When heat is absorbed on one side of a TEG (red arrow) the movable charge carriers begin to diffuse, resulting in a uniform concentration distribution in the TEG along the temperature gradient; and thereby producing a difference in the electrical potential on both sides of the TEG. To maximize the power generation output, P bars and N bars are connected together in a cell electrically in series and thermally parallel. Due to thermoelectric effect, electrons flow through the n type element to the colder side, while in the P type elements, the positive charge carriers flow to the cold side. These unit cells are assembled in long sequences to eventually build a TEG.

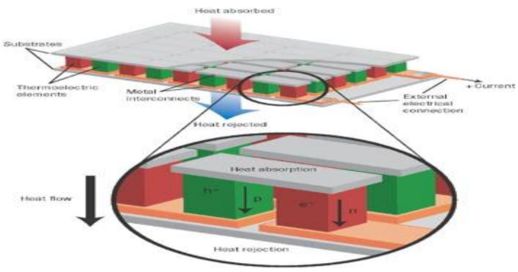

Fig (iii): Module working as a thermoelectric generator (© Nature Publishing Group, Jeff Snyder, Caltech)

A Peltier element is a thermoelectric cooler, or TEC, which is simply a small heat pump. A Peltier element works inversely to the Seebeck device and consist of a pair of semi-conductors which, when imposed by a direct current, generate a heat flow and a temperature difference between the two plates [1]. When a direct current is applied, one side absorbs heat (cold side) and the other side supplies heat (hot side). As an electric current is added to the Peltier element the unbound electrons in the N-type material are moving in one direction and the “holes” in the P-type material move in the opposite direction. If a voltage is applied from P- to N- material, electrons will move away from the junction in the N-type material and the “holes” will move away from the junction in the P-type material. The energy is “taken” from the junction area, which is cooled. On the opposite side the electrons and “holes” flow towards the junction heating it. A typical thermoelectric device consists of a number of cascaded thermo-conductor pairs arranged so that all the junctions one side are heated and the junctions on the other side are cooled. In this way a temperature difference is created between both sides of the module as displayed in Fig (iv) [5].

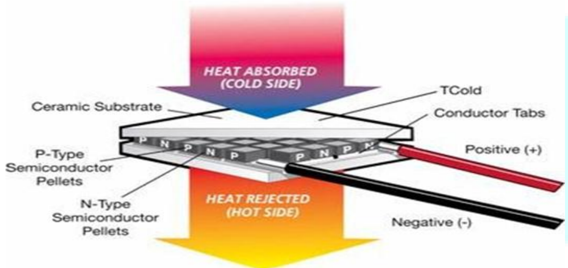

Fig (iv): Module working as a cooler(© http://www.tellurex.com/cthermo.html)

The advantages of thermo-electric modules are enumerated as follows.

- Extremely reliable (typically exceed 100,000 hours of steady-state operation) and silent in operation since they have no mechanical moving parts and require considerably less maintenance.
- Simple, compact and safe.
- Very small size and weight.
- Can operate at temperatures upto 70°C with a maximum temperature difference of about 67°C.
- Environment friendly.
- Position independent.
- Can act as flexible power sources.

III. BASIC WORKING

The main working of the proposed thermoelectric air cooler for trigeneration is as shown in the block diagram in Fig (v).

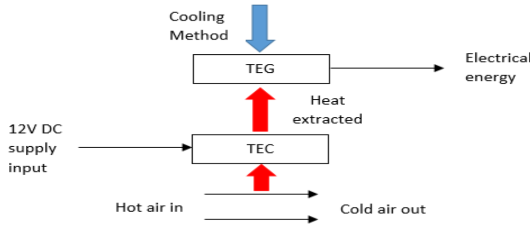

Fig (v): Trigeneration with TEC/TEG modules

A TEC is used to extract the heat from the air that is made to flow over its cold side by supplying its rated supply of 12V DC. After extraction of the heat, the air will emerge out at a comparatively lower temperature [3]. The extracted heat is then provided on to the hot side of a TEG and the other side of the TEG is maintained at a lower temperature with respect to that of the extracted heat by some cooling technique such as air cooling using heat sink [2] or by using water to cool the surface etc. This will create a temperature difference between the sides of the TEG which result in the generation of electricity [6].

Theoretically, a TEC can handle up to a maximum of 12V and 6A of current as its input supply. On providing this input, it maintains a temperature difference of approximately 60°C across its plates. Similarly, if a temperature difference of almost 60°C is obtained across the sides of the TEG, it would produce a voltage of 12V and a maximum current of 6A. But, practically, it is not possible to maintain such temperature differences for a long time under normal room temperature as the Peltier module itself conduct the heat from one side to the other. So, a lesser temperature difference of about 20°C is maintained by providing a voltage of about 12V and a current of 2A. A blower fan used in computers and other electronic devices can be used to provide the air flow on the cold side of the TEC. Overall, taking both the TEC and the fan, a total of 25W will be the power consumed by this air cooler as compared to the conventional air conditioners and coolers that needs a minimum of a 100W for their functioning. The proposed thermoelectric air cooler model is shown in Fig (vi).

The output of the TEG will depend on the temperature difference across its sides, number of TEG modules used and the connection configuration of the TEG modules. The number as well as the configuration depends on the application for which the output is being used.

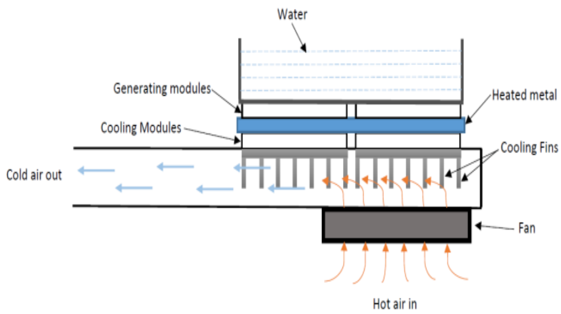

Fig (vi): Thermoelectric air cooler model

In an ideal case, if the temperature difference involved with the TEC of 24W is at 20°C, and if the same temperature difference is maintained across the TEG, it will also give an output power of 25W. But, it may not be practical to maintain the same temperature difference across the TEG plates. The output of the TEG will be only in the range of mW with its voltage of approximately 2-3V and current of up to 300mA. So, to make proper use of the output, the impedance of the TEG and the external circuitry must be matched. A TEG module has an impedance of 1.94Ω at 23°C and it increases with every degree rise in temperature. But the increase factor is negligible. So, the external circuitry must be designed to have an input impedance same as that of the TEG module as per the maximum power transfer theorem to get the necessary output. The number of TEGs can also be varied. The output depends on the connection configuration of the modules. The voltage increases as the number of modules in series combination increases and the current increases as the number of modules in the parallel combination increases. Since the produced output is of the order of millivolts, which is too small for lighting applications, a need arises to step-up the voltage. This can be done using two circuits namely, Joule thief circuit and an energy harvester circuit using LTC3109 IC.

IV. JOULE THIEF CIRCUIT

Joule Thief circuit is a simple voltage booster circuit. It can increase the voltage of a power source by changing the constant low voltage signal into a series of rapid pulses at a higher voltage.

Fig (vii) shows a simple joule thief circuit. Assume that the transistor is initially OFF. Current flows through the primary side of the transformer and through the 1k resistor, into the base of the transistor. The transistor turns ON slightly and produces a current in the collector emitter circuit. This allows current to flow in the secondary winding of the transformer and produces magnetic flux. This flux cuts the turns of the primary winding and produces a voltage that adds to the voltage produced by the battery.

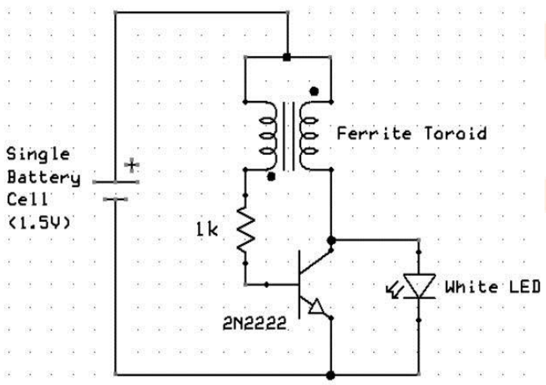

Fig (vii): Joule thief Circuit(© technologytutor.co.nz/wp-content/uploads/2012/07/Joule-Thief.jpg)

This increases the current into the base of the transistor and the transistors is driven into saturation region. At this point the magnetic flux in the secondary winding is a maximum, but it doesn't further increase and thus the primary winding does not produce any additional potential. The current into the base of the transistor reduces and the transistor move towards cut-off region .

The current through the secondary side of the winding reduces and the magnetic energy in the core of the ferrite ring starts to collapse and produce a voltage (in both windings) of opposite polarity. In the primary winding, it starts to turn the transistor OFF completely and in the secondary winding, it delivers this energy to the LED. Fig (viii) shows a joule thief circuit soldered.

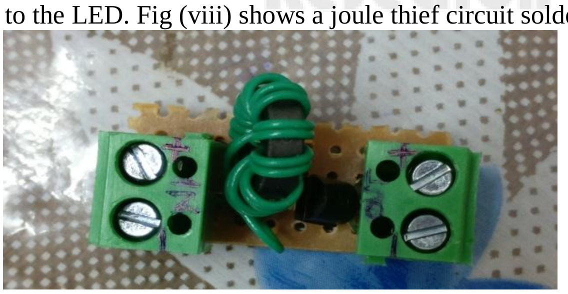

Fig (viii): Joule thief circuit on PCB

This circuit can step-up a voltage of 1V to about 3V . The impedance of the circuit should be matched with that of the TEG module by choosing proper transistors. But it has a disadvantage that it will operate only if the output of the TEG is enough to bias the transistor terminals. If the voltage is less than the bias voltage, then the circuit will not work.

V. LTC3109 ENERGY HARVESTER IC

A joule thief circuit will only start up its oscillations if the input voltage is above a voltage of about 0.8V. But this will also lead to loss in the form of heat energy. So to increase the efficiency, an ultra-low voltage energy harvester circuit using IC LTC3109 was used. The pin configuration of LTC3109 is shown in Fig (ix).

The LTC3109 is a highly integrated DC/DC converter ideal for harvesting surplus energy from extremely low input voltage sources such as TEGs (thermoelectric generators) and thermopiles. Its unique, proprietary auto polarity topology allows it to operate from input voltages as low as 30mV, regardless of polarity.

Using two compact step-up transformers and external energy storage elements, the LTC3109 provides a complete power management solution for wireless sensing and data acquisition. The 2.2V Low Dropout linear regulator Output can power an external microprocessor, while the main output can be programmed to one of four fixed voltages. The power good indicator signals that the main output is within regulation. A second output can be enabled by the host. A storage capacitor (or battery) can also be charged to provide power when the input voltage source is unavailable. Extremely low quiescent current and high efficiency maximizes the harvested energy available for the application.

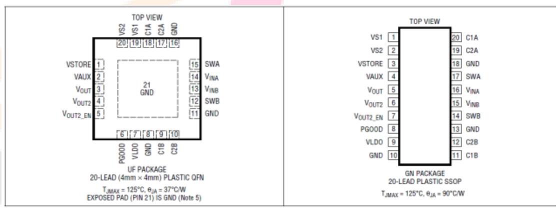

Fig (ix): Pin configuration of types of available LTC 3109(Picture Courtesy: Linear Technology, LTC3109, Auto-Polarity Ultralow Voltage Step-Up Converter and Power Manager, 3109fb.pdf)

The LTC3109 is designed to gather energy from very low input voltage sources and convert it to usable output voltages to power microprocessors, wireless transmitters and analog sensors. Its architecture is specifically tailored to applications where the input voltage polarity is unknown, or can change. This “auto-polarity” capability makes it ideally suited to energy harvesting applications using a TEG whose temperature difference may be of either polarity.

Fig (xi) shows LTC3109 circuit with two small external step-up transformers to create an ultra-low input voltage step-up DC/DC converter and power manager. It can operate from input voltages of either polarity. This unique capability enables energy harvesting from thermoelectric generators (TEGs) in applications where the temperature differential across the TEG may be of either (or unknown) polarity. It can also operate from low level AC sources. It is ideally suited for low power wireless sensors and other applications in which surplus energy harvesting is used to generate system power because traditional battery power is inconvenient or impractical. The LTC3109 is designed to manage the charging and regulation of multiple outputs in a system in which the average power draw is very low, but where periodic pulses of higher load current may be required. This is typical of wireless sensor applications, where the quiescent power draw is extremely low most of the time, except for transmit pulses when circuitry is powered up to make measurements and transmit data.

The LTC3109 can also be used to trickle charge a standard capacitor, super capacitor or rechargeable battery, using energy harvested from a TEG or low level AC source.

The LTC3109 utilizes MOSFET switches to form a resonant step-up oscillator that can operate from an input of both polarity using external step-up transformers and small coupling capacitors. This allows it to boost input voltages as low as 30mV high enough to provide multiple regulated output voltages for powering other circuits. The frequency of oscillation is determined by the inductance of the transformer secondary winding, and is typically in the range of 10 kHz to 100 kHz. For input voltages as low as 30mV, transformers with a turns ratio of about 1:100 is recommended. For operation from higher input voltages, this ratio can be lower.

The AC voltage produced on the secondary winding of the transformer is boosted and rectified using an external charge pump capacitor (from the secondary winding top in C1A or C1B in Fig(xi)) and the rectifiers internal to the LTC3109.The rectifier circuit feeds current into the V_{AUX} pin, providing charge to the external V_{AUX} capacitor and the other outputs. The active circuits within the LTC3109 are powered from V_{AUX}, which should be bypassed with a 1µF minimum capacitor. Once V_{AUX} exceeds 2.5V, the main V_{OUT} is allowed to start charging. An internal shunt regulator limits the maximum voltage on V_{AUX} to 5.25V typical. It shunts to ground any excess current into V_{AUX} when there is no load on the converter or the input source is generating more power than is required by the load. This current should be limited to15mA max.

The LTC3109 includes a precision, micro- power reference, for accurate regulated output voltages. This reference becomes active as soon as V_{AUX} exceeds 2V. Once V_{AUX} exceeds 2V, synchronous rectifiers in parallel with each of the internal rectifier diodes take over the job of rectifying the input voltage at pins C1A and C1B, improving the efficiency. The LTC3109 includes a low current Low Dropout linear regulated Output(LDO) to provide a regulated 2.2V output for powering low power processors or other low power ICs. The LDO is powered by the higher of V_{AUX} or V_{OUT}. This enables it to become active as soon as V_{AUX} has charged to 2.3V, while the V_{OUT} storage capacitor is still charging. In the event of a step load on the LDO output, current can come from the main V_{OUT} reservoir capacitor. The LDO requires a 2.2µF ceramic capacitor for stability. Larger capacitor values can be used without limitation, but will increase the time it takes for all the outputs to charge up. The LDO output is current limited to 5mA minimum.

The main output voltage on V_{OUT} is charged from the V_{AUX} supply, and is user-programmed to one of four regulated voltages using the voltage select pins V_{S1} and V_{S2}, according to Fig (x). Although the logic-threshold voltage for V_{S1} and V_{S2} is 0.85V typical, it is recommended that they be tied to ground or V_{AUX}.

VS2	VS1	V_{OUT}
GND	GND	2.35V
GND	VAUX	3.3V
VAUX	GND	4.1V
VAUX	VAUX	5V

Fig (x): Connection details for different voltage outputs. (Picture Courtesy: Linear Technology, LTC3109, Auto-Polarity Ultralow Voltage Step-Up Converter and Power Manager, 3109fb.pdf)

When the output voltage drops slightly below the regulated value, the charging current will be enabled as long as V_{AUX} is greater than 2.5V. Once V_{OUT} has reached the proper value, the charging current is turned off. The resulting ripple on V_{OUT} is typically less than 20mV peak to peak. The internal programmable resistor divider, controlled byVS1 and VS2, sets V_{OUT}, eliminating the need for very high value external resistors that are susceptible to noise pickup and board leakages. In a typical application, a reservoir capacitor (typically a few hundred microfarads) is connected to V_{OUT}. As soon as V_{AUX} exceeds 2.5V, the V_{OUT} capacitor will begin to charge up to its regulated voltage. The current available to charge the capacitor will depend on the input voltage and transformer turns ratio, but is limited to about 15mA typical. Note that for very low input voltages, this current may be in the range of 1µA to 1000µA.

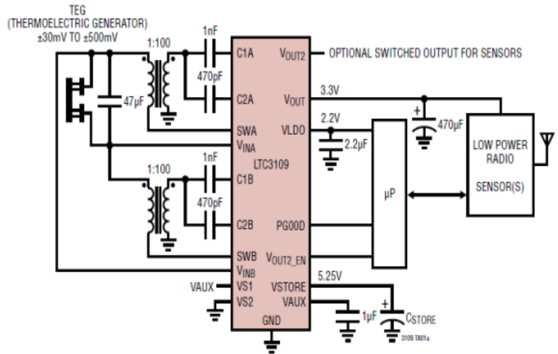

Fig (xi): Bipolar Configuration of LTC 3109 for TEG (Picture Courtesy: Linear Technology, LTC3109, Auto-Polarity Ultralow Voltage Step-Up Converter and Power Manager, 3109fb.pdf)

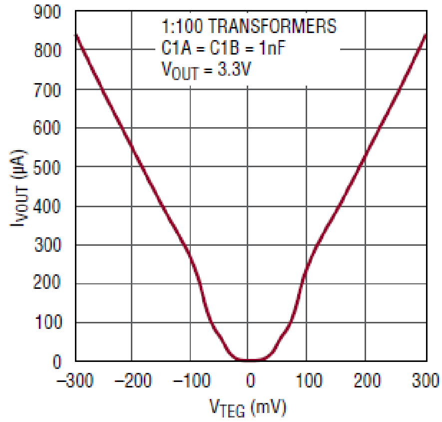

Fig (xii): V_{OUT} current vs TEG voltage plot(Picture Courtesy: Linear Technology, LTC3109, Auto-Polarity Ultralow Voltage Step-Up Converter and Power Manager, 3109fb.pdf)

The 5V output configuration can be used to charge a mobile phone via a USB cable as it is of the proper conditions as that of a standard USB port with 5V. Since the current will be very small of the order of a few 100mA, the charging process will take a longer time compared to the standard 230V 50Hz AC supply charger. The main advantage is that the charging can be done at a low consumption as the whole setup will draw only about 25W. Fig (xii) shows a typical plot of TEG voltage versus output current [9].

VI. CONCLUSION

Our basic work deals with the concept of trigeneration utilizing commercially available TEC/TEG modules and state of the art energy harvesting circuits. Further research is going on to develop energy efficient and environmental friendly power generators for small lighting applications, at the same time providing air cooling effect. This innovative idea will be commercialised in the near future as the concept of thermoelectric power generation gains popularity due its advantages of low cost, portability and durability compared to other conventional energy generation schemes. Also, as a future scope to this concept, a self-sustained air cooler can also be idealized as the generated power can be utilized to power the same air cooling device, thus making it self-sustained without the need for any external supply.

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