Charging and Discharging of Electric Battery with Thermoelectric Stove

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Abstract: Lithium batteries are featured by high specific energy, high efficiency and long life. These properties have made lithium batteries the preferred energy sources for the consumer electronics market with the production of billions of units annually. These batteries are playing a prominent role as ideal electrochemical storage systems in renewable power plants as well as power systems for sustainable vehicles, such as hybrid and electric vehicles.

This work focuses on charging and discharging batteries that store the generated electricity from the TEG to enable using it. One of the most advantage of the stove is that it doesn’t need maintenance because there is no moving part. Moreover, it should be workable day or night and will not be affected by the weather, the sun or anything other than the solar panels that work only on sunny days.

This will help us to reduce the battery capacity needed. The charging of the battery occurs only when the voltage of TEGs becomes more than the voltage of battery, and It was discovered that at temperature gradients below \( \Delta T_{\text{TEG}} = 100\; ^\circ\text{C} \), it was beneficial to employ a SEPIC DC–DC converter.

Keywords: Thermoelectric generator, battery, Lithium-ion battery, JUST stove.

1. INTRODUCTION

With the increase in energy demand and the expected shortage of the fossil fuel with time, the need for sustainable resources increases. Hence, this is initially handled by using clean fuels [1], utilization of waste heat [2-6] and adopting different configurations [7-9], where resources and environment are conserved.

According to a report from an estimated study established in 13 October 2016 by International Energy Agency (IEA) Sub-Saharan Africa faces what some energy analysts have shown that around 66% of the region’s population – more than 620 million people – have no access to electricity [10].

The TEG is a semiconductor device which converts thermal energy directly into electrical energy. A TEG consists of a number of cubical semiconductors blocks. It appears like a plate. The heat is applied to one face of it and the other face is kept relatively cool [11].

In this case, the major advantage of a TE generator is virtually maintenance-free, as there are no moving parts. Only the battery should be charged when needed. The TE generator operates day and night in clear or rainy weather, unlike solar panels. In addition, the battery does not need to be oversized [12].

The maximum power of the TEG can be reached when the load resistance corresponds to the internal resistance of the module. Unfortunately, the voltage at maximum power is usually different from the voltage required by the loads [13]. To keep the module operating at maximum power, it may be necessary to increase or decrease the voltage of the modules to power the loads. The power management will need to detect the situation of the modules and make appropriate changes to the power distribution. The DC / DC converter is needed to regulate the voltage and store electricity in a battery so that electricity is available all day. The thermoelectric generator (TEG) produces energy only when the stove is running. A variety of commercial batteries are available such as lead acid batteries, nickel metal hydride batteries and lithium iron phosphate batteries. Several characteristics need to be evaluated for battery selection such as cost, energy density, risks, and life cycles. To obtain maximum power from the TEG, the effective resistance of the battery must be comparable to the internal resistance of the TEG, and the DC-DC converter must change the impedance of the load, then implement a device for tracking the power point maximum (MPPT) to continuously monitor the maximum power point [13]. Vieira and Mota [14] designed and built a maximum power point tracker to optimally charge a lead acid battery using a thermoelectric module. The MPPT was based on a single ended primary inductor converter (SEPIC) circuit working in continuous conduction mode and the Perturb and Observe method was used to find the maximum power point. In the algorithm, charge protection was also implemented to protect the lead...
acid battery from over-charging. The experimental results showed that if the 12 V battery was directly connected to the TEG, the TEG generates 19 W, whereas if the MPPT was inserted between the TEG and the battery, the TEG produces 28.5 W. The MPPT circuit produces 33% more power from the TEG than direct charging.

In fact, we will not be able to burn fuel all the time. In addition, the electricity produced by the stove can not be used simultaneously. It then becomes necessary to store energy until needed. Hence the need to research the use of the battery to achieve this goal.

2. OVERVIEW OF THERMOELECTRICITY

The electrical efficiency of the stove-based TEG system depends on two main factors: The efficiency of the TEG and the temperature difference between the two ends. The first is based on the efficiency of the thermoelectric materials and the last on the temperature level and the rate of thermal conduction through the TEG [13].

The thermoelectric device can convert the thermal energy of a temperature gradient into electrical energy. This phenomenon was discovered in 1821 and is called "Seebeck effect". It is used for energy production. The inverse counterpart of this phenomenon was discovered by Peltier in 1834 and used for cooling [15].

Thermoelectric generators are solid state energy devices that convert heat directly into electricity through the thermoelectric effect. TEGs have no moving parts and are commercially available in a variety of shapes, sizes and power ratings. The operating principle is illustrated in Figure 1. A thermoelectric module is interposed between a heat source and a heat sink. Heat flows from the heat source through the module and is dissipated by the heat sink, and electricity is generated by the module. The thermoelectric module consists of pairs of thermal elements p-n. The positive (p-type) and negative (n-type) doped semiconductor elements are electrically connected in series and thermally in parallel [16].

Initially, the conductors in the module possess a uniform distribution of charge carriers. However, the heat input to the module, \( Q_H \) creates a temperature difference across the p-n thermos elements.

The Seebeck effect is described as the free carriers at the hot end and has greater kinetic energy to diffuse at the cold end. Charge buildup creates a back that resists charge flow. If the temperature difference between these junctions is maintained, an open circuit voltage \( V_{oc} \) is generated in accordance with

\[
V_{oc} = \alpha (T_h - T_c)
\]

Where \( \alpha \) is the Seebeck coefficient and \( T_h \) and \( T_c \) are the "hot" and "cold" junction temperatures. The Seebeck coefficient is a property of thermoelectric material.

![Figure 1: Thermoelectric power generation](image)

The equivalent circuit for a thermoelectric module can be represented by a voltage source, \( V_{oc} \) with a variable resistor in series \( R_{int} \) as shown in Figure 2.

For this study, a rechargeable battery must be charged using the TEG as the power source. Therefore, to obtain maximum power from the TEG, the effective resistance of the battery must be comparable to the internal resistance of the TEG. In this study, we select a battery with the same effective resistance as the internal resistance of the TEG.

The disadvantage is that the internal resistance of the TEG changes with the temperature while the effective resistance of the battery changes with the charging current [16].

3. THERMOELECTRIC MODULE SELECTION

The choice of the correct module size can only be made with a thorough analysis of the heat sink. For a given heat sink, the higher power modules actually
make less power than the modules with lower power ratings because the larger modules have a smaller thermal resistance for shorter legs and fewer elements, resulting in a much smaller temperature difference. In addition, the efficiency is significantly reduced at lower temperatures. Therefore, the low temperature module will have to move much more heat to make the same power. Beyond cost and efficiency, the operating temperature is an important factor for the durability of the TE module because high temperature generator modules can withstand high temperature and compensate with a dramatic increase in power.

The thermoelectric module chosen for this investigation was the TEG SP1848-27145 supplied by Thermal Electronics Corp, China. As shown in Figure 4.

The TEG is composed of ceramic/ Bismuth Telluride p-n junctions. While TEGs with larger area specify higher output power per degree temperature difference, a greater heat is required to maintain the same $\Delta T_{\text{TEG}}$. Some specifications for the module are provided in Table 1.

Table 1: TEG Module Characteristics

| Model characteristic     | Symbol | Value | Unit |
|--------------------------|--------|-------|------|
| Maximum power            | $P$    | 3.21  | W    |
| Load resistance          | $R_L$  | 6.8   | $\Omega$ |
| Internal resistance      | $R_i$  | 6.8   | $\Omega$ |
| No. of semiconducting pairs | $N$ | 12   | KW   |
| Thermal conductance      | $U_{\text{pn}}$ | 0.85 |      |

Other specifications from the manufacture:
Model: SP1848-27145
Color: White

Material: Ceramic / Bismuth Telluride
Module weight: 25g
Module size: 4 x 4 x 0.34cm (L x W x H)
Cable length: 30cm

4. BATTERIES

4.1. Basics of Batteries

The battery is the heart of the vehicle’s electrical system. It powers lights, heat sources, fuel heaters, starter and charge systems and other accessories.

It acts as a voltage stabilizer for the electrical system and provides power when the electrical demand exceeds the output of the charging system.

The main task of the battery in a diesel powered electric system is to start the engine. It must provide high current to the starter for a short time.
The electric starter starts or turns the steering wheel and crankshaft until the vehicle starts.

A battery stores chemical energy. When connected to electrical load, such as a starter motor or glow plug, a reaction occurs in the battery that converts that chemical energy into electrical energy. Once the materials used to produce this chemical reaction are exhausted, the flow of current ceases. However, these materials can be restored by forcing DC power into the battery.

4.1.1. Battery Design

Batteries can be grouped into three major types: conventional, low maintenance, and maintenance free. All type shares many common design characteristics. All batteries contain grids of positive and negative plates. Each grid holds the active materials needed for the chemical reaction that produces electrical power. A positive plate is made of grid filled with lead peroxide (PbO2) as its active material. A negative plate is made of grid filled with sponge lead (Pb).

4.1.2. Elements and Cells

A battery element is a group of alternative positive and negative plates, each welded to a post strap. A separator of insulation material such as porous fiberglass or polyethylene is placed between the plates. Each element is placed inside the battery case and immersed in an electrolyte solution composed of water (H2O) and sulfuric acid (H2SO4). The sulfuric acid supplies sulfates that chemically react with the lead (Pb) and the lead peroxide (PbO2) on the plates to release electrical energy. The electrolyte also carries the electrons inside the battery between the negative and the positive plates.

During this chemical reaction, negative charged ions accumulate on the negative plates and positively charged ions on the positive plates. The negatively charged ions have an excess of electrons, while the positively charged ions have a lack of electrons. When an electrical circuit is closed, the excess electrons pass through the circuit from the negative to the positive plates. As long as the circuit is closed, current will pass from negative plates to positive plates.

Once a battery element is placed in electrolyte and becomes chemically active, is called a cell. The battery case has a number of individual cell compartments. Cell connectors are used to join battery cells in series with one another. Each cell has an open circuit voltage of approximately 2.1 volts. A 12-volt storage battery with 6 cells connected in series has an actual open circuit voltage 12.6 volt when fully charged.

The top of the battery is covered by a cell cover. The cell cover may be a one-piece design, or each cell may have its own cover. Conventional and low maintenance batteries must have vents in their cell covers. The vent holes provide access to the cell for adding water or electrolyte.

They also permit the escape of hydrogen and oxygen gases that form during charging and discharging.

The battery has two external terminals: a positive terminal (+) and a negative terminal (−). Terminals can be top-mounted tapered posts, threaded studs, or side mounted internally threaded connectors. Terminals connect to either end of series of elements inside the battery and are clearly marked either (+) or (−). In many batteries the positive terminal is slightly larger in diameter to minimize the danger of installing the battery cables in reverse polarity.

4.2. Types of Batteries

4.2.1. Lead-Acid Battery

The lead-acid battery is frequently used in automobiles and other applications in which weight is
not a concern. In the 1970s, the valve-regulated lead-acid battery (or the "sealed lead-acid battery") was developed; this battery used a gel electrolyte instead of a liquid, allowing the battery to be used in a variety of positions without introducing leakage. In the battery’s discharged state, both the positive and negative plates are lead sulfate \((\text{PbSO}_4)\), and the electrolyte is primarily water, having lost most of its dissolved sulfuric acid \((\text{H}_2\text{SO}_4)\) [18].

The discharge process is moving by the conduction of electrons from the negative plate to the positive plate through an external circuit. In the charged state, each cell contains negative plates of elemental lead \((\text{Pb})\) and positive plates of lead oxide \((\text{PbO}_2)\) in a sulfuric acid electrolyte. The charging process is moving by the forcible removal of electrons from the positive plate and the forcible introduction of them to the negative plate using a charging source. There are several types of lead-acid batteries, and the type most suited for use with renewable energy systems is the deep discharge type because this design is intended to provide small amounts of power continuously over long periods and discharge up to 80% of the total battery capacity without damaging the battery [19].

### 4.2.2. Lithium Battery

A lithium ion battery includes at least one battery cell. The battery cell includes a cathode electrode, an anode electrode, and a separator. The separator is sandwiched between the cathode electrode and the anode electrode. At least one of the cathode electrode and the anode electrode includes a current collector. The current collector is a graphene layer [20].

The demand for electro-chemical power cells, such as Lithium-ion batteries, is ever increasing due to the growth of applications such as electric vehicles and grid storage systems, as well as other multi-cell battery applications, such as electric bikes, uninterrupted power battery systems, and lead acid replacement batteries. It is a requirement for these applications that the energy and power densities are high, but just as important, if not more, are the requirements of low cost manufacturing and increased safety to enable broad commercial adoption. There is further a need to tailor the energy to power ratios of these batteries to that of the application [21].

When comparing performance parameters of small and large cells relative to each other, it can be found that small cells in general have higher gravimetric \((\text{Wh/kg})\) and volumetric \((\text{Wh/L})\) capacity compared to large cells. It is easier to group multiples of small cells using binning techniques for capacity and impedance and thereby matching the entire distribution of a production run in a more efficient way, compared to large cells. This results in higher manufacturing yields during battery pack mass production. In addition, it is easier to arrange small cells in volumetrically efficient arrays that limit cascading runaway reactions of a battery pack, ignited by for instance an internal short in one cell (one of the most common issue in the field for safety issues). Further, there is a cost advantage of using small cells as production methods are well established at high yield by the industry and failure rates are low. Machinery is readily available, and cost has been driven out of the manufacturing system [22].

On the other hand, the advantage of large cells is the ease of assembly for battery pack OEMs, which can experience a more robust large format structure which often has room for common electromechanical connectors that are easier to use and the apparent fewer cells that enables effective pack manufacturing without having to address the multiple issues and know-how that is required to assemble an array of small cells.

In order to take advantage of the benefits of using small cells to create batteries of a larger size and higher power/energy capability, but with better safety and lower manufacturing costs, as compared to large cells, assemblies of small cells in a multi-core (MC) cell structure have been developed [23].

Lithium batteries are available in both primary and secondary style (rechargeable and non rechargeable). Lithium batteries are backup power source for electronic equipment that can be divided in two large groups: those providing full backup power to run a price of equipment. Instead it serves as a long-term power source so that the memory components can retain necessary information.

Lithium batteries consist of a cathode, and a lithium anode, which is an organic electrolyte that conducts the current. Lithium cobalt oxide is a material from which lithium can be easily removed. The charged lithium ions are driven from the cathode into the anode; when the charge is removed, the lithium returns to the cathode [24].

There are many styles of lithium primary batteries, they all long operational life over a wide range of operating temperature, and provide long-term storage life at room temperature.
Common type of primary lithium batteries includes: lithium sulfur dioxide (Li$_2$SO$_4$), lithium thionyl chloride (LiSOCl$_2$), lithium manganese dioxide (LiMnO$_2$), lithium carbon monofluoride (Li (CF)$_3$), lithium copper oxide (LiCuO), and lithium iodine (LiI$_2$).

Common type of secondary lithium batteries includes: lithium iron sulfide (LiFeS$_2$), lithium manganese titanium (LiMnTi), lithium polymer, lithium ion, lithium vanadium pentoxide (LiV$_2$O$_5$), lithium manganese dioxide (LiMnO$_2$) and lithium titanium disulfide (LiTiS$_2$) [25].

4.3. Storage Battery Power Ratings

12-volt electrical system on passenger cars has emphasized the need for specific power rating for storage batteries of different voltages. When only 6-volt batteries are considered, ampere-hour ratings give a satisfactory comparison of the available energy. For example, when a 6-volt battery of 100 ampere-hour capacity, is compared to 6-volt battery having 110 ampere-hour capacity, it becomes evident that the battery having the greater weight of lead produces the greater ampere-hour capacity. A comparison of ampere-hour capacity of 6- and 12-volt batteries, however, can be quite misleading [26].

Consider, for example, 12-volt battery illustrated. This model has 11 plates in each of its 6 cells and a rating of 70 ampere-hour. Since ampere-hour capacity depends on weight of material, a 6-volt battery with the same number of similar plates in each of its 3 cells would also have a rating of 70 ampere-hour. But, if the total of 66 plates used in the 12-volt battery were divide equally between 3 cells, the unit would theoretically be a "22 plate" 6-volt battery and would produce twice the capacity or 140 ampere-hour. Thus, the extra "power" available from the 3 additional cells in the 12-volt battery does not show up in the ampere-hour rating. However, if we consider the effect of voltage on the ampere-hour produced, the extra power becomes evident [26].

Since power is a product of amperes times volts (amperes x volts = watts) a fundamental basis for comparing batteries can be established by multiplying ampere-hour ratings by voltage (ampere-hour x volts = watt-hours). On this basis a 100 ampere-hour 6-volt battery is rated at 600 watt-hours. by comparison, a 70 ampere-hour, 12-volt battery is rated at 840 watt-hours. Consequently, the power rating in watt hours makes possible a direct comparison between the 12-volt battery and the 6-volt battery.

Ampere-hour ratings still have a useful application in determining a suitable slow or normal charge rate for any given battery. In the past, a rate of one ampere per positive plate per cell was considered satisfactory for standard size plates. However, such a rule may cause overcharging on more recent batteries containing narrow, thin or short plate. The current rule is to use 7% of the ampere-hour to get the normal slow charge rate [26].

4.4. Charging and Discharging of Batteries

4.4.1. Battery Capacity, Discharge Current, and Charge Current

Electrical batteries are DC storage systems that can either store or produce electrical energy by chemical transformations. The process of storing energy is called 'charging', whereas the production of energy is called 'discharge'. The chemical transformations are proportional to the amount of current consumed, respectively produced, in Ah, corresponding to Faraday's laws. Therefore, the size of a battery is given in Ah (amperes (A) x time (h)). As the capacity is dependent on the discharge current and the duration of discharge, it is not a constant value. This can be derived by the designation given by the manufacturers. The nominal capacity is given for 5 hours discharge time ($C_5$) for vehicle batteries and NiCd batteries; whereas for stationary batteries (also common for gas-tight NiCd batteries) the 10-hour discharge capacity ($C_{10}$) is given; and for starter batteries, motorcycle batteries, and small lead-acid accumulators the capacity for a 20-hour discharge ($C_{20}$) is given. A $C_5$ of 100 Ah signifies that this battery produces 100 Ah during 5 hours of discharge and the 5-hour discharge current is $I_5 = 100/5 = 20$ A. The corresponding discharge current ($I_5$, $I_{10}$) is also a measure for the charging current. If a charging current of $2 \times I_5$ is mentioned, this means that charging is conducted with twice the $5$-hour discharge current. For a capacity of 100 Ah this amounts to $2 \times 100/5 = 10$ A [27].

4.4.2. Charge Coefficient

The ratio of amount of current needed for full recharge to the drawn current is called the charge coefficient. It amounts to 1.1–1.2 for lead-acid batteries depending on their design and between 1.2 and 1.4 for NiCd accumulators. During every charging process a part of the applied amount of energy is lost, especially above the gassing voltage, through the process of chemical decomposition of water and hydrogen in the electrolyte. Therefore, a greater amount of energy must
be applied for charging than has been drawn prior to recharge. For example, given a battery with a nominal capacity of 125 Ah; 80% discharged (100 Ah); with a charging coefficient of 1.2; in order to attain fully charged state, 100 Ah x 1.2 = 120 Ah have to be provided [28].

4.4.3. Charging Time

The given charging times are idealized calculated values presuming that all battery and rectifier-specific data are constant. Practically such conditions are not met as, for example, mains fluctuations influence uncontrolled chargers; aging of the battery and variant temperatures also have influence. Variance of the electrolytes temperature by 10°C (reference temperature for traction batteries 30°C (86°F), for stationary batteries 20°C and for starter batteries 27°C) changes the charging time by 1 hour. If the temperature is lower than the corresponding reference temperature as above, then charging is prolonged, whereas higher temperature shortens charging time. As these disturbing variables cannot be controlled, they are not considered for calculations of the charging time. A variance of +0.5 hour of the charging time should therefore be expected [29].

4.5. State of Health (SOH)

SOH describes the physical state of the battery, starting from internal behavior, such as loss of capacity, to external behavior, such as extreme conditions [30]. Unlike SOC, there is no clear-cut definition of SOH. The general definition of SOH is that it reflects the health status of the battery and its ability to deliver specific performance compared to a new battery [31, 32]. The SOH in EV applications are used to characterize the ability to drive a specific distance or range. SOH in HEV applications are a characteristic of the specified power, such as the cranking power from regenerative braking. Scholars and manufacturers use the percentage of nominal capacity as the health threshold of the battery [33]. When the capacity decreases to 80% of the start-of-life capacity after the charge-discharge cycle, it is defined as a battery failure. However, studies have defined different rules or indicators to quantify the SOH in terms of battery characteristics, test equipment, and different applications. Patinate et al. [32] combined capacity fade and power fade as health characteristics. Capacity fall indicates the decrease in the driving range with a fully charged battery pack, and power fall indicates the reduced acceleration capability. Both of these features were input into an auto-regressive Support Vector Regression (SVR) model to estimate SOH. Here, the power fade was due to an increase in cell impedance during aging.

Chao and Chen [35] designed a state of health estimator for lead-acid batteries. Coup de Fouet voltage [36], internal resistance and transient current, were input into a modified extension matter-element model to develop intelligent SOH evaluation [37].

5. EXPERIMENTAL PROCEDURE AND RESULTS

This work focuses on the charging and discharging of batteries that store the electricity generated by the TEG and how it can be used to provide the government with regular electricity to meet our major electricity needs.

The experiment is carried out on three types of fuels namely, wood, peat, and manure (horses) due to availability in deprived regions. They can be used without and no much further treatment.

1. The measurement of temperature along different position of the stove was taken using type-K thermocouples at different times in order to compare it with the theoretical data.

2. All temperature measurements were taken using a type-K thermocouple data logger.

3. On the TEG assembly, two sensors (ML35) are installed exactly at the hot and the cold side of the TEG model and the measurement were taken for $T_H$ and $T_C$.

4. All electrical quantities are measured using digital multi meter (DMM).

Figure 5: Charging battery versus Time.

Initially, the small battery (1.25 V lithium-ion battery) will not charge until the voltage of the TEG reaches more than the battery voltage, it is after 13 minutes
and charge continuously until the battery is full after 22.5 min. then began charging the large battery (3.7V lithium-ion battery) until the voltage of the TEG became greater than the large battery voltage of 2.67V appeared at 25.5min. then charge continuously until the battery is fully charged.

6. CONCLUSIONS

1. A lithium ion battery comprising at least one battery cell, the battery cell includes a cathode electrode, an anode electrode, and a separator.

2. The evolution of the lithium ion battery is open to innovations that will place it in top position as the
battery of the future, Especially after development hybrid and electric vehicles.

3. A battery stores chemical energy. When connected to electrical load, such as a starter motor or glow plug, a reaction occurs in the battery that converts this chemical energy into electrical energy.

4. The electrical efficiency of the stove-based TEG system depends on two main factors: the TEGs efficiency and the temperature difference between two ends.

5. The advantage of the TE battery-charger system using MPPT is that the system can charge the battery by using the heat energy directly.

6. The charging of the battery occurs only when the Voltage of TEGs becomes larger than the voltage of battery.

7. It was discovered that at temperature gradients below $\Delta T_{TEG} = 100^\circ C$, it was beneficial to employ a SEPIC DC–DC converter. However above $\Delta T_{TEG} = 100^\circ C$, more power was delivered to the battery by direct charging.

HIGHLIGHTS

• Small amounts of electrical power are generated using the thermoelectric effect.

• The electricity produced is used to charge rechargeable 1.25 - 3.7 V Lithium-ion batteries.

• The evolution of the lithium ion battery is open to innovations that will place it in top position as the battery of the future.

• DC-DC converter is recommended for temperature gradients less than 100 C°

NOMENCLATURE

\[ I = \text{current, A} \]
\[ N = \text{number of thermoelectric models} \]
\[ Q_C = \text{heat dissipated from TEG cold side, W} \]
\[ Q_H = \text{heat delivered to TEG hot side, W} \]
\[ R_L = \text{load resistance, } \Omega \]
\[ T_c = \text{module cold side temperature, K} \]
\[ T_h = \text{module hot side temperature, K} \]
\[ V_{oc} = \text{open circuit voltage, V} \]

GREEK SYMBOL

\[ \alpha = \text{thermoelectric material Seebeck coefficient (V/K)} \]
\[ \Delta T_{TEG} = \text{module temperature difference, K} \]

ABBREVIATIONS

JUST = Jordan university of science and technology
MPPT = maximum power point tracking
SEPIC = single ended primary inductor convertor
SOH = state of health
TEG = thermoelectric generator

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