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Development of Peltier Cooling and Thermoelectric Generation based Storage System

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Abstract—Storage is going to be a crucial part of the electrical grid of the future, with the penetration of renewables. It is necessary to have a long-term storage method to take care of seasonal variations of Solar Energy. The system must be environmentally friendly and must not have hazardous materials. A thermoelectric storage system is proposed in this work to take care of these challenges. Cooling of a Phase Change Material can be done via Peltier modules and the energy to supply latent heat of fusion can be considered as the charging process. By operating the Peltier modules as a thermoelectric generator (i.e. Seeback Effect) the discharging of the cell can be done. The system must be suitably insulated to prevent heat loss. Coefficient of performance and efficiencies of the thermoelectric modules may be a deterrent but by modulating power judiciously via Power Electronics the technology can be scaled up.

Keywords—Storage, Peltier Cooling, Thermoelectric (TEC) Generation, Solar Photovoltaic Integration

I. INTRODUCTION

This paper introduces the concept of Energy Storage by Cooling a Phase Change Material (PCM) below ambient by the Peltier Effect (Charging) and using the Temperature gradient to drive a Thermoelectric Generator (Discharging) [1]. In this work the thermal and electrical model of the Thermoelectric Module is discussed and an estimate of the round-trip efficiency of such a storage system is determined. A lab scale prototype of the thermoelectric cell is developed for experimental validation. For long term storage, efforts need to be taken to insulate the system from Heat entering the system to maintain the cold temperature of the PCM.

A major area where this system could find application is in Solar PV System Design. Such a system could be used as the second level of long-term storage when the primary storage resource has been depleted. Usually Solar PV Standalone systems are designed to handle worst case insolation conditions in Winter or Rainy seasons and therefore in summer excess electricity generated is wasted as PV panels must be operated below Maximum Power Point. Also, in the low insolation periods there are phases of Loss of Power as the State of Charge of the Primary Storage falls below the lower limit.

The excess energy could be used to continuously charge the system via Peltier Cooling and the energy stored could be used during loss of load phases by Thermoelectric Generation. A side advantage of this system is that the Cold PCM can be also used for serving cooling loads when required. It should be added that for such a system to be successful for long term storage, the thermal insulation must be near perfect and ambient temperature should not have large variations as there has to be enough temperature gradient for thermoelectric generation.

II. THERMOELECTRIC CELL

The basic cell would consist of a thermally sealed container, so that heat would not conduct back into the system. The size of the container is 1000 cc. A single Thermo-electric Module is mounted on the top. The container is filled with the fluid to be cooled (in this case water). The hot junction of the Thermoelectric Module is fitted with a Heat Sink and Fan Assembly. Temperature sensors are attached to the cold junction and heat sink surface.

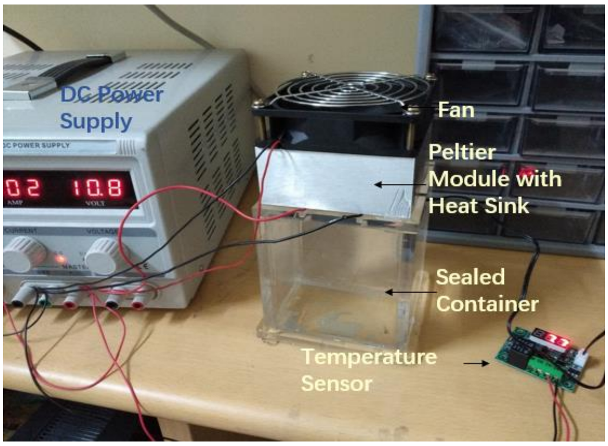

Fig. 1. Prototype of Thermoelectric Cell

The experimentaly observed readings are shown in Table 1. The Cold Junction Temperature reached was 5°C. Output Power obtained by Thermoelectric Generator was 150mW. This was low due to single thermoelectric generator power output limitation. With more modules covering the entire surface the Power Output can be scaled up. There is a tradeoff between maximum power required and time scale for which storage is required. During Cooling as temperature gradient between hot and cold side increases, more input electrical power is required to bring about the same cooling effect. To maintain constant Cooling Load the current has to be modulated. Cooling Load (W) $=Q_c = f(V, I, \Delta T)$. Performance Curves of the Peltier Modules show that when ΔT is small the ratio of cooling load to input power (i.e. Coefficient of Performance COP) is large but as ΔT increases COP decreases. While charging we need to consider specific heat of cooling and latent heat separately. Charging will be complete once latent heat is fully supplied.

TABLE I. EXPERIMENTAL RESULTS

State	**Experimental Results**	
	Parameter	***Value***
Charging	Minimum Temperature of Cold Side Achieved:	5°C
	Ambient Temperature:	28°C
	Cooling Power Input:	60W
Discharging	Maximum Thermoelectric Generator Output Power:	150mW
	TEG Open Circuit Voltage:	1V
	TEG Short Circuit Current:	600mA

Discharging process is the action of Thermoelectric generator (TEG). The higher the temperature gradient higher is the power that can be generated. There is a trade-off between COP of cooling and efficiency of TEG for a temperature gradient. If temperature gradient is too high TEG efficiency will be higher but COP of cooling will be lower and vice versa. A standard measure of the efficacy of storage system can be given by the charge to discharge efficiency which can be rudimentarily be written for the present system under study as $\mathrm{COP_{cooling}} \times \eta_{\mathrm{TEG}}$. Maximum Power Point Tracking (MPPT) must be utilized to operate the TEG module at Maximum Power Point Voltage and Current

III. THERMOELECTRIC MODEL

The cooling power of the Peltier Module is given by Q_c [2]-[3] as in (1). The electrical power input is given by W as in (2).

$$Q_c = \alpha I T_C - 0.5 I^2 R - k\Delta T \qquad (1)$$

$$W = I^2 R + \alpha I \Delta T \qquad (2)$$

Where α = Seeback Coefficient, k= Thermal Conductance, R= Resistance of Material

Current (I) is positive for Thermoelectric Cooling (Peltier Effect) and is negative for Thermoelectric Generation (Seeback Effect)

$$COP_{cooling} = \frac{Q_c}{W} \qquad (3)$$

$$COP_{max} = \frac{T_c}{T_H - T_c}\left(\frac{\sqrt{1+Z\overline{T}} - {}^{T_H}/_{T_C}}{\sqrt{1+Z\overline{T}}+1}\right) \qquad (4)$$

where $ZT = \frac{\alpha^2}{kR}$ (figure of merit)

$$\eta_{\mathrm{TEG}} = \frac{\mathrm{W}}{Q_c} \qquad (5)$$

$$\eta_{max} = \frac{T_H - T_c}{T_c}\left(\frac{\sqrt{1+Z\overline{T}}-1}{\sqrt{1+Z\overline{T}} + {}^{T_H}/_{T_C}}\right) \qquad (6)$$

The complete roundtrip efficiency is given by:

$$\eta_{\mathrm{Total}} = COP_{cooling} \times \eta_{\mathrm{TEG}}$$

$$= \frac{\sqrt{1+Z\overline{T}}-1}{\sqrt{1+Z\overline{T}}+1} \times \left(\frac{\sqrt{1+Z\overline{T}} - {}^{T_H}/_{T_C}}{\sqrt{1+Z\overline{T}} + {}^{T_H}/_{T_C}}\right) \qquad (7)$$

TABLE II. EXAMPLE CALCULATIONS

Parameter	**Value**
T_H T_C $\overline{T}$ $Z\overline{T}$	300 K 273 K 286 K 1
η_{TEG} $COP_{cooling}$ η_{Total}	1.6% 1.32 2.11%

The calculations are shown for a TEG module with ZT of 1, with a temperature gradient of 27°C in Table 2. The thermoelectric generator efficiency was 1.6% and COP of cooling was 1.32 [4]-[6]. The overall roundtrip efficiency for a storage system with these specifications would be around 2%. This is a very small value and hence such a system would be preferable as a secondary level of storage only. We will corroborate a useful application for this system in a PV standalone Microgrid. It should be mentioned that this system would not require any complicated technology except for the Power Electronics and the TE interface and can operate on a long term basis.

IV. INTERFACING WITH PV

The Thermoelectric Storage System can be well suited for a Standalone PV System as will be explained. The specifications of the system are as follows according to optimal sizing. The system sizing and simulation is done in HOMER Pro microgrid design optimization software:

1. Location: Bangalore, India
2. Annual Energy Consumption = 800 kWh
3. Size of PV Unit = 1kW
4. Size of Primary Battery Storage = 5kWh

TABLE III. SYSTEM PARAMETERS

Parameter	**Value**
Annual Load Served	800 kWh
Annual PV Power Generated	1500 kWh
Annual Excess Energy	600 kWh
Annual Unmet Electrical Load	12 kWh

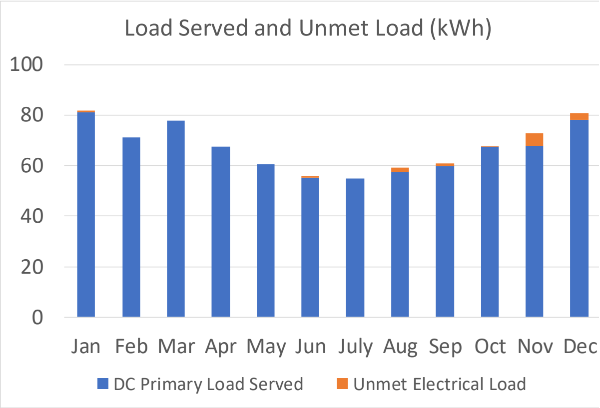

Fig. 2. Load Served and Unmet Load for Standalone PV System

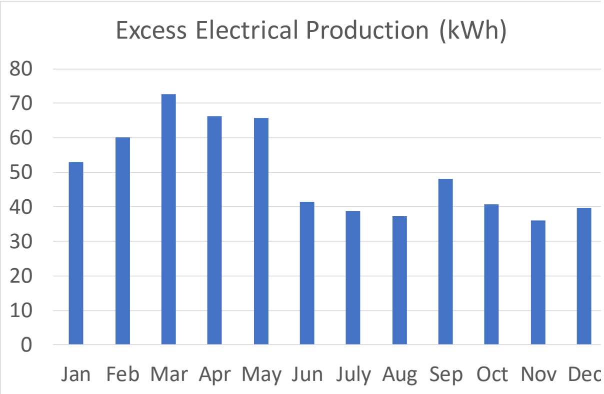

Fig. 3. Excess Electrical Production for Standalone PV System

As can be seen in the Fig. 2 the months of low insolation [Nov, Dec, Jan (Winter), Aug-Rainy] has Unmet Load for a small proportion of the time. Also, according to Fig.3 there is excess electrical energy production from the PV modules in almost all months of the year. In the proposed solution the excess electricity generation can be used to charge the Thermoelectric Storage system. Assuming insulation of the storage system is enough as that there is no heat loss, we can get back 2% of 600kWh of energy which amounts to 12kWh. This is equal to 12kWh which is sufficient to cater the unmet electrical load. Thus, theoretically there will be no loss of load throughout the year.

V. SYSTEM DESIGN

The Power Electronics and Control Strategy for the PV based Thermoelectric Storage System is discussed in this section. The three segments of the system are the Solar PV stage, the Li Ion Battery Stage and the Thermoelectric Storage Stage. The Solar PV stage operates at Maximum Power Point and is an uncontrolled power generator. The Battery Storage is a controlled source and maintains the DC bus voltage. The Thermoelectric (TEC) Generation stage operates when State of Charge (SoC) falls below the specified limit (5% in this example). Also, the Peltier Cooling (TEC charging) operation continues in the background whenever excess power is available. The functional block diagram of the system is shown in Fig. 4.

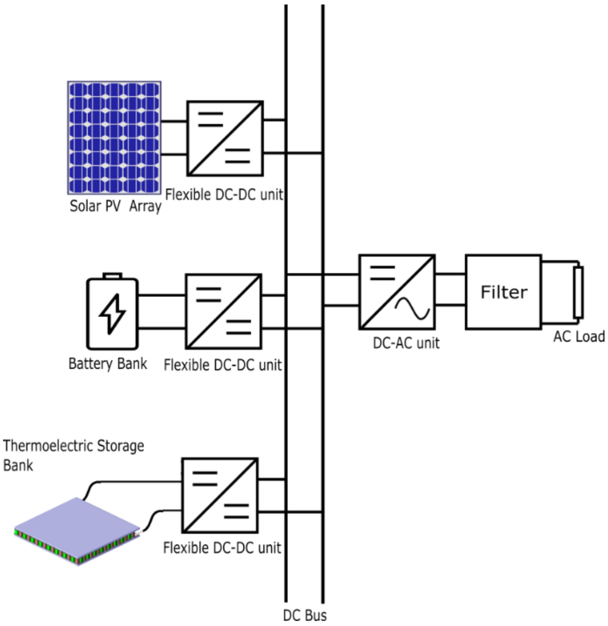

Fig. 4. Functional System Block Diagram

The basic circuit diagram is shown in Fig. 5. The system consists of identical modular non-inverting DC-DC buck boost converters for the PV, Battery and the Thermoelectric stages [7]. The PV power is maintained at MPP by the Perturb and Observe Algorithm. This happens if SoC is within its maximum limit. If SoC goes above the maximum limit (95% in this example) it automatically moves away from the MPP to maintain SoC at the maximum value. The Control Loops are shown in Fig. 6.

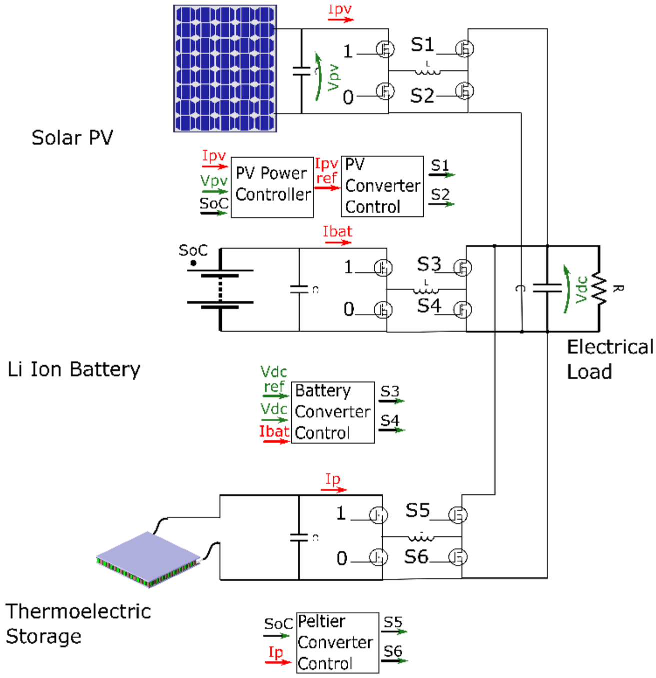

Fig. 5. Circuit and Control Block Diagram

The Battery Bidirectional Controller maintains the DC link voltage at the set point value. The charging and discharging currents are set by the system power balance. The Outer DC link voltage controller gives the battery current reference to the inner current control loop. When the SoC goes below the minimum level the battery should be protected from over discharge, so the Thermoelectric Generation is enabled to recharge the Battery System.

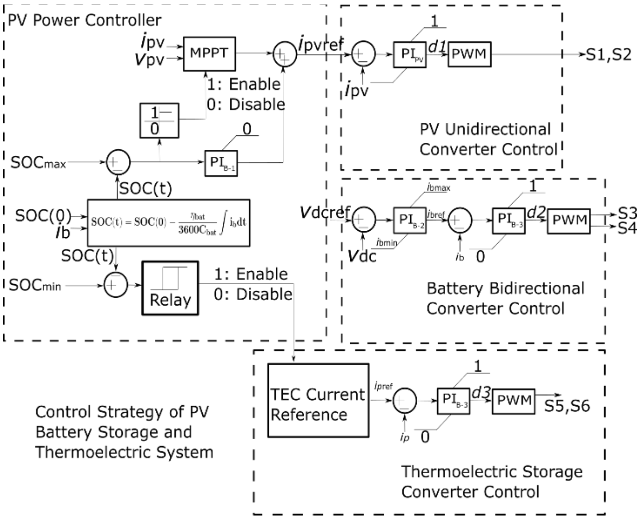

Fig. 6. Control Block Diagram

The system was simulated in MATLAB/Simulink Environment. The load was maintained at 250W. To demonstrate the working of the Thermoelectric system. The PV generation was operated at low insolation level of 100W/m^2 so that the battery discharges. The output power from PV at this insolation is around 90W as seen in Fig. 7. Once the SoC reaches close to 5% the Thermoelectric Generation is enabled. Hence the Li Ion Battery now starts recharging as seen in Fig. 8 and Fig. 9. The Thermoelectric Voltages and Currents are shown in Fig. 10. The Li Ion Battery is thus prevented from over discharge and the load is also simultaneously met.

Power Balance during Battery Discharging:

Load Power (250W) = Solar PV Power (90W) + Peltier Cooling Load (-100W) + Battery Discharge (260W)

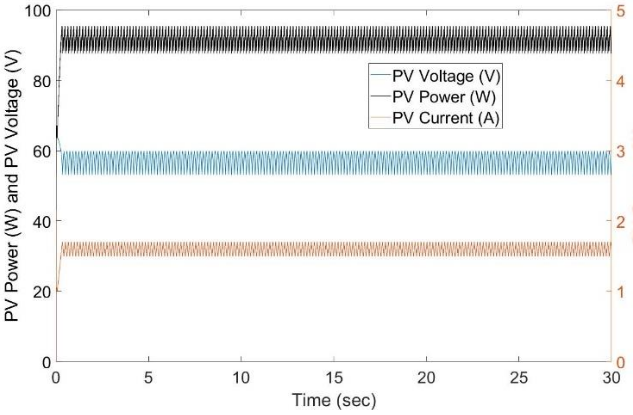

Fig. 7. PV Stage Voltage, Current and Power

Power Balance during Battery Charging:

Load Power (250W) = Solar PV Power (90W) + Peltier Cooling Load (250W) + Battery Charge (-90W)

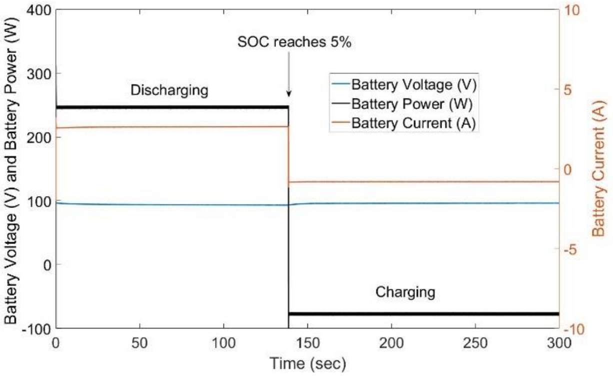

Fig. 8. Battery Stage Voltage, Current and Power

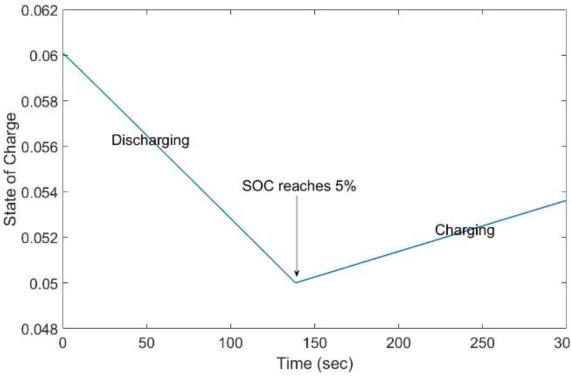

Fig. 9. State of Charge

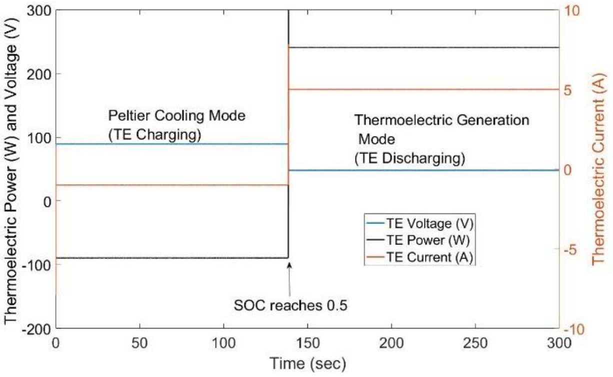

Fig. 10. Thermoelectric Stage Voltage, Current and Power

VI. CONCLUSIONS

A Peltier Cooling and Thermoelectric Generation based Storage System is proposed. The experimental setup for a Thermoelectric Cell is developed. The Charging and Discharging Processes is described. The model of the Thermoelectric system is developed to estimate the round-trip efficiency of the storage system. An application for this storage system is proposed for Standalone PV systems. The excess energy from the PV modules is used to charge the storage (Peltier Cooling) and the unmet load is taken care by the Thermoelectric Generation. The Power Electronics for the system is proposed by using modular DC-DC noninverting buck boost converters. The system is simulated to demonstrate it is implementable. The control strategy automatically modulates the power balance of the system to provide maximum availability of Power. The Peltier Cooled PCM could also be used for meeting the Cooling requirements of the premises. Further research efforts are required on this concept to demonstrate feasibility at the kW level.

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