

Voltage Controlled DC-DC Converter for Enhancing Waste Heat Recovery

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Abstract- The waste heat is a main concern that effect the efficiency of almost all the equipment's we come across. The waste heat retrieval using thermoelectric modules(TEM) can increase the efficiency of the overall system, not in a high amount but 3% to 7%. The efficiency and output voltage profile of TEM is very low. Appropriate power control circuitry is needed to utilize this waste heat. The paper discusses a voltage controlled single switch converter, to utilize the heat recovered for low voltage DC (LVDC) applications. A hybrid topology incorporating a SEPIC and Boost converter . The converter is suitable for TEM applications. The voltage control is simpler and is implemented using PI controller. The TEM is modelled and the closed loop converter is simulated MATLAB\SIMULINK.

Index Terms- Thermoelectric Module (TEM) ; PCU ; LVDC ; SEPIC.

1. INTRODUCTION

The demand for electricity is increasing day by day. In the recent years with the advancement of electronic equipment's there is a transition from AC to DC power usage. Today DC loads have substituted most of the conventional AC loads in our private houses and larger (commercial and office) buildings. DC power is produced locally and consumed locally. In a developing country like India the main beneficiaries of the LVDC is the household utilities. The installations of parallel networks of AC and LVDC distribution systems is a conceivable "transition solution". It is possible to connect different DC sources to a DC grid without a synchronization procedure. This enable the integration of different renewable sources. This paper deals with the production of LVDC using the waste heat recovery.

Heating is a major problem which we are concern with most of the equipment's, what if the wasted heat can be used as the useful energy?. In the day to day life in houses and commercial buildings a lot of heat is emitted from refrigerator , water heater , air conditioner and among others as waste heat. Recovering this heat into usable electricity would save a significant amount of money through increasing efficiency. The increase in efficiency is not a huge amount but only a 3% to 7% increase. Even this increase in efficiency is beneficial as it is from a free source and can contribute to the overall system efficiency.

Due to the prevalence of semiconductor the thermoelectric material was made with n and p type structures . Several thermoelectric materials are connected in series to increase the operating voltage.

TEGs generate electrical energy using Seebeck effect from a temperature gradient.

There are mainly four basic components in a TEM. Heat source , TE element , cold side and a Power control unit (DC-DC converter). Various mathematical model for the TEM has evolved over time. Models have been developed to simulate there behaviour and analyse the performance.[1],[2] Equivalent circuit SPICE models of TEMs have been recently developed [3][4], which are suitable for simulation of power-electronics applications. A simple model of TEM using MATLAB/SIMULINK is build in this paper. In order to integrate the TEM with DC grid of 48v a voltage controlled DC DC converter is necessary. Several topologies of boost converter has evolved over time. Basic energy storing elements, in conjunction with switch(es) and diode(s) are utilized in the circuit. Various topologies are incorporating switched capacitor cell [5], switched inductor cells[7] or coupled inductor[9] in the conventional topologies.

The main constraints on the selection of converter are switch stress, current ripple and EMI. A SEPIC converter is a topology that make a compromise on all these constraints. Various modifications on the SEPIC converter has been introduced in order to increase the step up capability[11] and also for power factor correction[12]. Introduction of diode capacitor[13] in the converter topologies provides an added advantage of reducing the switch stress. Hybrid topology[14] is in which different converter are connected in a hybrid fashion. This helps to extract the advantages of both the converters. The paper is dealing with DC DC converter which is a hybrid topology of Sepic and Boost converter with diode capacitor technique a

single Switch [15].The voltage mode control is using PI controller.

The paper is organised in the following way, Section II deals with the modelling of TEG, Section III deals with the DC DC converter and control Section IV deals with the simulation results.

2. TEM MODEL BUILDING

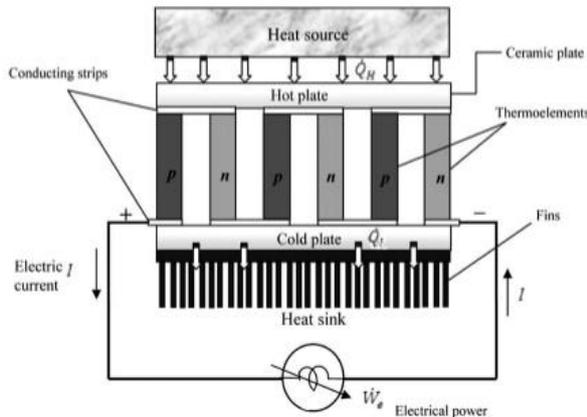


Fig. 1. Schematic diagram of a TEG

The principle of operation is based on the seebeck effect. Two dissimilar metals which are joined together and subjected to a temperature difference produces a small amount of electrical when connected to a resistive load. The series connection of n-type and p-type semiconductor make a couple. Figure 1 shows the basic structure of a TEG. Depending on the required voltage level thermoelectric generators are connected in series as a module. A TEM with a 6V voltage and 15W power is modelled in this paper.

The TEM undergoes mainly four energy processes: thermal conduction, Joule heating, the Peltier cooling/heating effect, and the Seebeck effect. The thermal conductivity (K_{th}) of the material describes the thermal conduction. The dissipation of heat in the resistive element results in Joule heating. The dissipation of heat as a result of current flow through the junction is Peltier heat effect. For steady-state analysis, the both sides of the TEM, is considered to be in energy equilibrium. The heat generated at hot side and emitted at cold side is given by Q_H and Q_C respectively, given by

$$Q_H = SIT_A - .5I^2R + K_{th}\Delta T \quad (1)$$

$$Q_C = SIT_E + .5I^2R + K_{th}\Delta T \quad (2)$$

The TEM's output voltage is given as

$$V = U_S + IR \quad (3)$$

U_S is the Seebeck voltage given by

$$U_S = S\Delta T \quad (4)$$

Where S is the Seebeck constant.

A large Seebeck coefficient (S) with low electrical resistance (R) and low thermal conductivity (K_{th}) are the desirable features for a TEM. The figure-of-merit (FOM) parameter is then defined as

$$Z = \frac{S^2}{RK_{th}} \quad (5)$$

The operating temperature considered for the model is $T_h = 230^\circ\text{C}$ and $T_c = 30^\circ\text{C}$, The required output power and voltage is selected as $V_m = 6\text{V}$ and $P_m = 15\text{W}$.

The electrical resistance can be easily expressed as

$$R = \frac{V_m^2}{P_m} \quad (6)$$

The efficiency is a function of load resistance R_L , it is defined as $R_L = mR$, m is the resistance ratio. The maximum efficiency is taken as 4.5% as same as the HZ-20 module. The thermal efficiency of a TEG is defined as the ratio of the electric power output to the thermal power input to the hot side, which can be expressed as

$$\eta = \frac{I^2 R_L}{Q_H} \quad (7)$$

The maximum efficiency is obtained at an optimal resistance ratio m_{opt} given as

$$m_{opt} = (\Delta T + \eta^{max}T_C)/(\Delta T - \eta^{max}T_H) \quad (8)$$

The FOM of TEM is then obtained as

$$Z = (m_{opt}^2 - 1)/T_{avg} \quad (9)$$

$$T_{avg} = .5(T_H + T_C) \quad (10)$$

The thermal conductivity K_{th} is calculated as

$$K_{th} = \frac{S^2}{RZ} \quad (11)$$

The current I can be obtained by

$$I = (S\Delta T)/[(1 + m_{opt})R] \quad (12)$$

The Seebeck constant can be computed for our required conditions $V_m = 6\text{V}$, $T_H = 230^\circ\text{C}$, $T_C = 30^\circ\text{C}$

$$S = \frac{2V_m}{\Delta T} \quad (13)$$

The voltage output can be obtained as

$$V_L = S\Delta T - IR \quad (14)$$

The MATLAB/SIMULINK model is implemented by realizing these equations using basic SIMULINK blocks. The SIMULINK model of TEM is given in figure 2

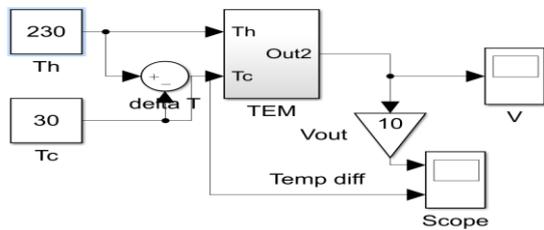


Fig 2(a): Subsystem model of TEM

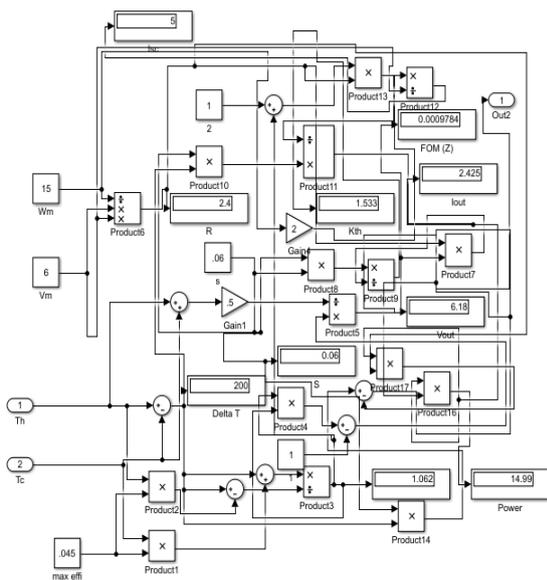


Fig 2(b) : Detailed model of TEM in SIMULINK

3. DC DC CONVERTER TOPOLOGY

The circuit topology of converter is shown in Fig.3. It consists of dc voltage source V_{in} , main switch S , three diodes D_1 , D_2 , and D_3 , three capacitors C_1 , C_2 , and C_3 , two inductors L_1 and L_2 , output diode D_0 , and capacitor output C_0 . A diode-capacitor

element is introduced in the topology to reduce the stress across the power devices and to increase the static gain. Inductor L_2 gets charged from the capacitor C_2 , which is the output of the boost converter. This make an increase in gain when compare to conventional SEPIC.

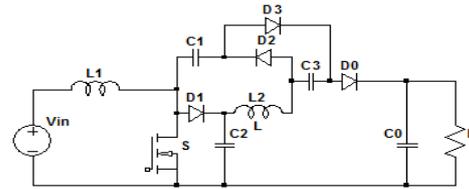


Fig 3 : Circuit topology of the converter[15]

A continuous conduction mode of operation is considered and has four modes of operations.

Mode 1 and *Mode 2* is lasting for a small amount of time and is not considered for steady state analysis. In both the modes the switch S is in ON condition. The *Mode 1* ends when the diode D_3 is reverse biased and the *Mode 2* ends when the diode D_2 becomes forward biased. Figure 4 and 5 gives the circuit topologies for *Mode 1* and *Mode 2*.

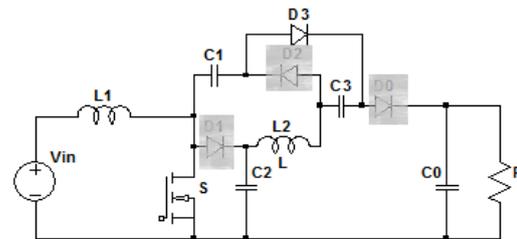


Fig 4: Mode 1

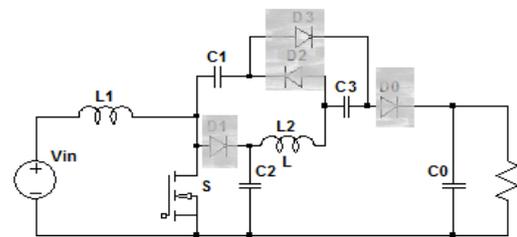


Fig 5: Mode 2

Mode III :In this mode, the switch S remains in on condition and diode D_2 is in forward biased condition and all other diodes are in OFF condition as shown in Fig.6. The supply and capacitor C_2 charges the inductors L_1 and L_2 respectively. The load is supplied by the discharging of capacitor C_0 . The switch S is turned OFF resulting in the termination of this mode.

Mode IV: In this mode, the switch S and diode D_2 is remains OFF and all other diodes are in ON condition as shown in Fig. 7. Both the inductors L_1 and L_2 starts discharging in the reverse polarity. The discharge current through L_1 charges the capacitor C_2 . The output capacitor C_0 and load R are getting charged from The capacitor C_3 charges the output capacitor through diode D_0 . The switch S is turned ON at the next period.

Component	Design equation
Inductor 1 (L_1)	$(V_{in}D)/(\Delta I_{L1}f_s)$
Inductor 2 (L_2)	$(V_{C2}(1 - D))/(\Delta I_{L2}f_s)$
Capacitors C_1, C_2, C_3	$(I_{out}D)/(\Delta V_c f_s)$
Output capacitor C_0	$(I_{out}D)/(\Delta V_0 f_s)$

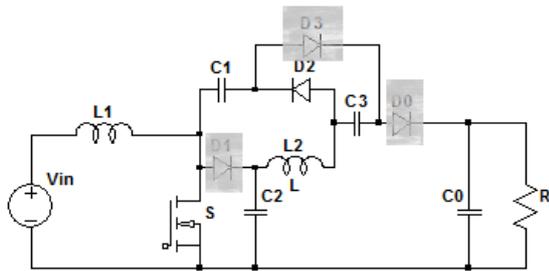


Fig 6: Mode 3

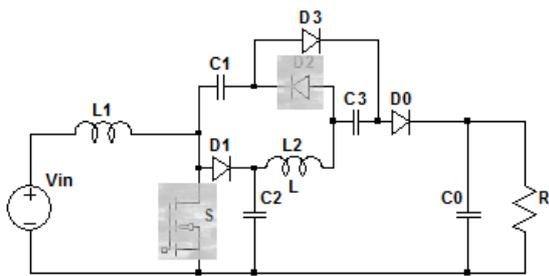


Fig 7: Mode 4

The voltage in power switch S and the diodes D_1 and D_0 are equal to the capacitor C_2 voltage. The output voltage is equal to the sum of the capacitors C_1 and C_2 voltage, when the switch is turned off and expressed as:

$$V_{out} = V_{C1} + V_{C2} \quad (15)$$

The capacitor C_2 and C_3 voltages as given below

$$\frac{V_{C2}}{V_{in}} = \frac{1}{1-D} \quad (16)$$

$$\frac{V_{C3}}{V_{in}} = \frac{1}{2(1-D)} \quad (17)$$

The static gain of the converter is obtained by assuming average inductors voltage as zero at steady state condition. The voltage gain is obtained as

$$\frac{V_0}{V_{in}} = \frac{3+D}{2(1-D)} \quad (18)$$

The equations used to select the components are derived from the current and voltage ripple equations.

Table 1 shows the design equations for the components in the circuit

D is the duty ratio of the switch. ΔI_{L1} and ΔI_{L2} are the current ripples of the inductors L_1 and L_2 respectively. ΔV_c and ΔV_0 are the voltage ripple across the capacitor C_2 and output capacitor respectively.

TABLE 1: COMPONENT DESIGN

D is the duty ratio of the switch. ΔI_{L1} and ΔI_{L2} are the current ripples of the inductors L_1 and L_2 respectively. ΔV_c and ΔV_0 are the voltage ripple across the capacitor C_2 and output capacitor respectively.

The switching voltage is an important parameter of a circuit which increases the converter cost and efficiency. The converter in this paper drastically reduces the high switching voltage compared with conventional boost and SEPIC converter. The switching voltage of converter is equal to the capacitor C_2 voltage.

A 48V DC is considered as the standard for Low voltage DC applications. The output voltage of the converter should be maintained as constant, as the voltage of the DC grid i.e 48V. On/off, PID controllers are simple and used commonly. The Fuzzy and neural controllers are complex, and use more classy concepts like artificial intelligence. In this project, the entire focus is on the feedback control system that uses the PI algorithm. PI stands for proportional and integral. The PI algorithm is easy to understand theoretically and implement practically.

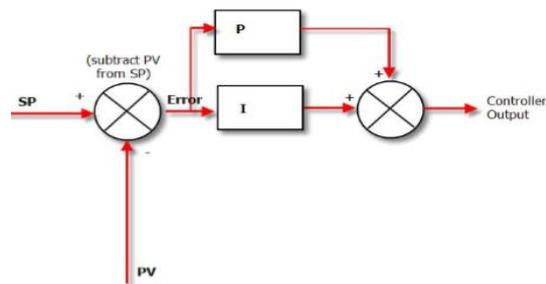


Fig 8: Basic block diagram of a PI controller

The output of the converter is feed backed and compared with a setpoint value. The error generated is sent to the PI controller. The output of a controller is given to a PWM modulator. The control input is the duty ratio 'D'. As the output changes from set value the controller changes the duty ratio D of the converter and bring the output back to the set point value. Figure 8 shows a basic block of PI controller

The value of the P and I gain can be calculated in a many ways conventional method is using Ziegler

Necholas method but this method requires more complex mathematical calculations. So the gain can be computed using simulation tool in Simulink using trail and error by adjusting the Step response cure bodeplot, root locus or auto tuning method by linearizing the plant.

4. SIMULATION RESULT

In order to validate designed model the TEM along with the converter is simulated using MATLAB/SIMULINK.

4.1. Thermoelectric generator

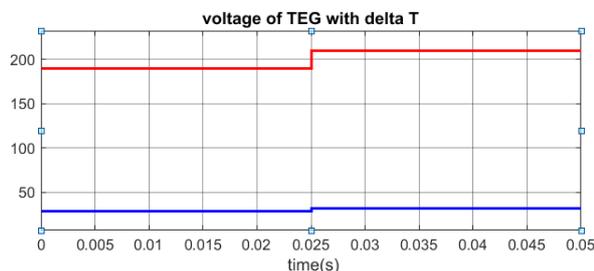


Fig. 9. Plot of Output voltage of TEG with temperature difference

The figure 9 shows the plot of Output voltage of the TEG with the temperature difference. The output voltage raises in proportional to the temperature difference. Reaches the required 6V at the operating temperature 230°C

4.2. DC DC Converter.

The Simulation of converter is done in both open loop and closed loop. Parameter values are selected as given in table 2. The frequency is selected to be 25KHz. $V_{in} = 6V$ and $V_{out} = 48V$.

TABLE 2 . MAIN PARAMETERS

Parameter	Value
Inductor L_1	128 μ H
Inductor L_2	74 μ H
Capacitor C_1, C_2, C_3	3.6 μ F
Capacitor C_0	22 μ F

The open loop simulation results of the converter is shown in figure 10

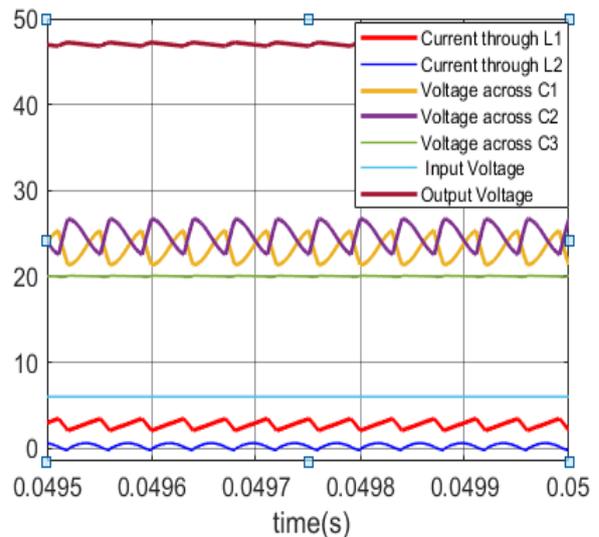


Fig 10: Open loop simulation result of Converter

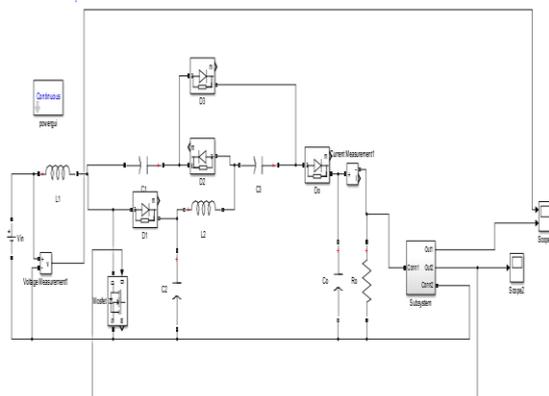


Fig 11: The closed loop system

The Figure 11 shows a closed loop system in which the controller is shown as a subsystem.

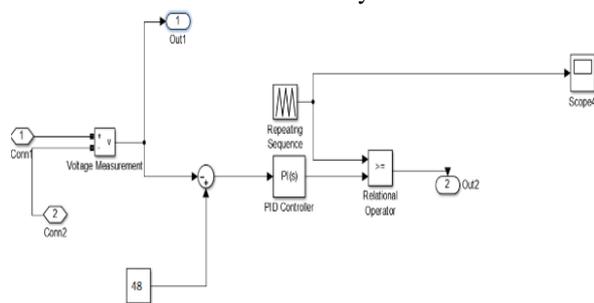


Fig 12: The controller Simulink model

The controller model is shown in figure 12. The output voltage is compared with a desired 48V and error is given to a PI controller.

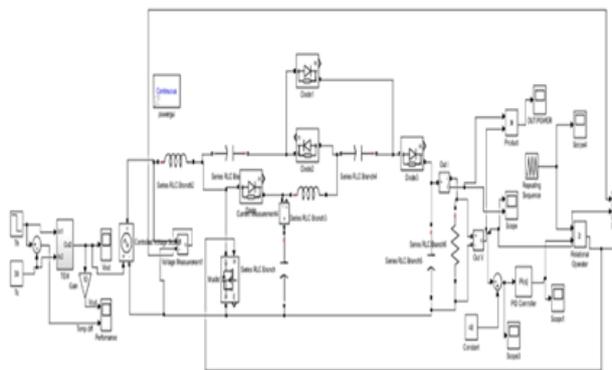


Fig 13: The Converter with integrated TEM module

The converter with input side integrated with TEM is shown in figure 13.

Figure 14 shows the waveform of output voltage with change in the temperature difference. As the temperature difference changes the input voltage (a gain of 5 is given for clarity) changes still the output voltage remains at 48V

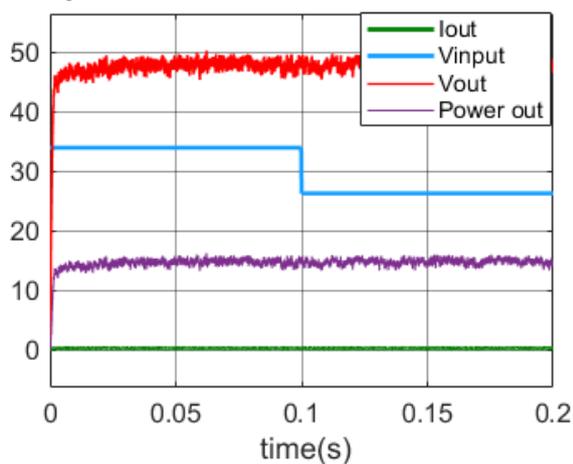


Fig 14: Output voltage with change in temperature

Figure 15 shows the Output voltage at constant temperature difference and at rated load the output voltage remains constant at 48V.

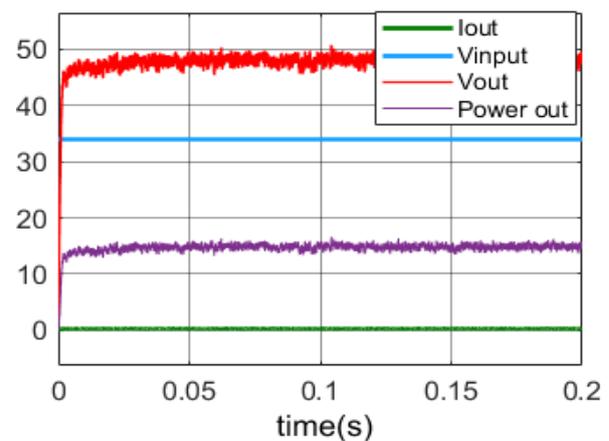


Fig. 15: Output voltage with constant temperature at rated load

Figure 16 shows the Output voltage at constant temperature difference and at nearly no load the output voltage still remains constant at 48V.

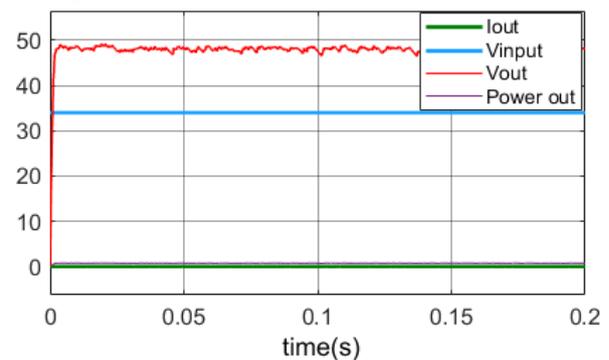


Fig. 16: Output voltage with constant temperature at no load

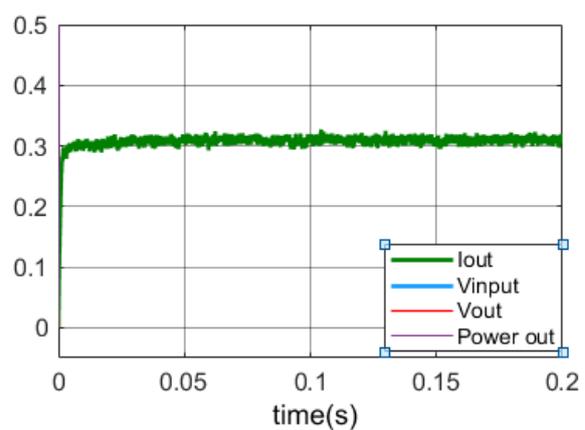


Fig. 17: Zoomed view of current at rated load

Figure 17 and 18 shows the zoomed view of current at rated load and no load the figure 13 to 17 validates the line regulation and load regulation of the converter.

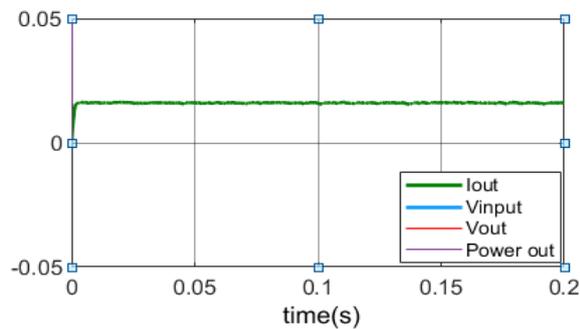


Fig. 18: Zoomed view of current at no load

5. CONCLUSION

For integration of the TEG modules with the electronic circuit the proper knowledge of their behavior and the performance analysis is required. The model build here is simple to implement and well-matched with Matlab/Simulink libraries for further simulation. A dc-dc converter with high static gain having a single switch is presented in this paper. The converter topology is suitable for renewable energy based applications having low input dc voltage. The converter provides high voltage conversion without using transformer and coupled inductor. The semiconductor power devices used in this topology having reduced voltage stress. The control using PI is simple and provides a constant DC output.

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