

THERMOELECTRIC POWER GENERATOR FOR AUTOMOTIVE APPLICATIONS

VOLKAN AKDOGAN

BSc, MSc

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Abstract

A thermoelectric generator (TEG) converts thermal energy into electrical energy corresponding to temperature gradient across both hot and cold surfaces with a conversion efficiency of approximately 5%. In spite of the conversion efficiency, TEGs can be implemented effectively for waste heat recovery systems within the power rating of kilowatts. The insufficiency of natural resources, frequently increasing oil costs and emission regulations have become an incentive factor of the recent increased interest in TEG applications.

This thesis introduces a practical implementation of the thermoelectric generator for an automotive exhaust system which has a rapid transient response to produce electrical energy from the waste heat which flows through the exhaust pipe. In addition to automotive TE power generator implementation, an H-Bridge DC-DC converter within the operation of maximum power point tracking method is introduced in this thesis to obtain the maximum power transfer between the thermoelectric power generator and the load.

This thesis presents a transient solution to the two-dimensional heat transfer equation with variant ambient temperature that determines heat transfer and electrical potential across the thermoelectric pellet. This equation is applied into a designed two-dimensional heat transfer MATLAB model and a comparison of simulation and experimental results approves the accuracy of the designed model. In addition to heat transfer simulation, a dynamic large scale thermoelectric power generator simulation program is introduced in this thesis to provide data analysis of actual implementation.

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Abbreviations

Thermal Abbreviations

α	(V/K)	Seebeck coefficient
η	(%)	Efficiency
ρ	($\Omega \cdot m$)	Resistivity,
τ		Thompson coefficient, RC time constant
Δ		Difference
Π		Peltier coefficient
A	(m^2)	Area
c_p	(J / kg °C)	Specific heat capacity
dx		Infinitesimal length
h	(W/($m^2 \cdot K$))	heat transfer coefficient
H	(kJ/kg)	Enthalpy
K	(W/m.K)	Thermal conductivity
K	(W/K)	Thermal conductance

l	(m)	Length
L	(m)	Total length
$\dot{m}$	(kg/s)	Mass flow rate
N_u		Nusselt number
P	(Pa)	Pressure
P_e		Péclet number
P_r		Prandtl number
q	(W/m ²)	Heat flux
Q	(W)	Heat energy
Q_{exhaust}	(W)	Heat loss to the exhaust
Q_{coolant}	(W)	Heat loss to the coolant
R_a		Rayleigh number
R_e		Reynolds number
t	(s)	Time
T	(K)	Temperature
u	(J)	Internal energy, velocity
1-D		One Dimensional

2-D	Two Dimensional
3-D	Three Dimensional
A/D	Analogue to Digital
CAT	Catalytic Converter
CFD	Computational Fluid Dynamics
COP	Coefficient of Performance
EGR	Exhaust Gas Recirculation
GE	General Electrics
GM	General Motors
GUI	Graphical User Interface
HP	High Pressure
ICE	Internal Combustion Engines
LP	Low Pressure
I/O	Input/Output
NASA	National Aeronautics and Space Administration
NEDC	New European Drive Cycle
NI	National Instruments

RT	Real Time
RTG	Radioisotope Thermo-electric Generator
TC	Thermocouple
TE	Thermoelectric
TEG	Thermoelectric Generator
TEM	Thermoelectric Module
USA	United States of America
Z	Thermo-electric figure of merit
ZT	Non-dimensionless thermo-electric figure of merit

Electrical Abbreviations

ADC	Analogue-to-Digital Conversion
CCM	Continuous Conduction Mode
C_{GD}	(F) Gate-drain (Miller) capacitance of a MOSFET
C_{LOAD}	(F) Capacity of the load filter capacitor
C_{OUT}	(F) Capacity of the output filter capacitor

D		Duty cycle of a PWM signal
D/A		Digital to Analogue
DAQ		Data Acquisition system
DC		Direct Current
DCM		Discontinuous Conduction Mode
ESC		Extremum Seeking
Edrv	(J)	Energy dissipated by the MOSFET gate drivers
f_{sw}	(Hz)	Frequency of a switching signal
f_{osc}	(Hz)	Frequency of the PWM oscillator
IC		Incremental Conductance
I_D	(A)	Current flowing in the drain of a MOSFET
I_{IN}	(A)	Input current
I_L	(A)	Current flowing through the inductor L
I_{LOAD}	(A)	Current consumed by the load
I_{OUT}	(A)	Output current
K	(J/K)	Boltzmann constant equal to $1.38 \cdot 10^{-23}$ J/K
M		MOSFET

M		Voltage conversion ratio in a DC-DC converter
M_{BOOST}		Voltage conversion ratio in a boost converter
M_{BUCK}		Voltage conversion ratio in a buck converter
$M_{\text{BUCK-BOOST}}$		Voltage conversion ratio in a buck-boost converter
MPP		Maximum Power Point
$MPPT$		Maximum Power Point Tracking
M_{SEPIC}		Voltage conversion ratio in a SEPIC converter
OC		Open Circuit
P	(W)	Power
PCB		Printed Circuit Board
$P_{\text{COND(TOT)}}$	(W)	Sum of the conduction losses in a DC-DC converter
P_{DS}	(W)	Drain-source switching losses
$P_{\text{DS(ON)}}$	(W)	Drain-source conduction losses
P_{drv}	(W)	Power losses in the MOSFET gate drivers
P_G	(W)	Power losses in the MOSFET due to gate capacity
P_{LOAD}	(W)	Power consumed by the load

P&O		Perturb & Observe
Poss	(W)	MOSFET drain-source capacitance output power losses
Prr	(W)	Body diode reverse recovery power losses in MOSFETs
Psw(tot)	(W)	Sum of the switching losses in a DC-DC converter
PV		Photovoltaic
PWM		Pulse Width Modulation
Q _G	(C)	Gate-charge capacitance of a MOSFET
Q _{oss}	(C)	Output charge of a MOSFET
q	(C)	Charge of an electron equal to $1.6 \cdot 10^{-19}$ C
R	(Ω)	Resistance
R _{IN}	(Ω)	Internal resistance
R _{LOAD}	(Ω)	Load resistance
R _{DS(on)}	(Ω)	Drain-Source resistance of a turned-on MOSFET
R _{FB}	(Ω)	Resistances controlling the gain of the feedback loop
RMS		Root Mean Square

SC		Short Circuit
T_A	(K)	Ambient air temperature
T_J	(K)	Junction temperature
t_{OFF}	(s)	Time during which the energizing switch is off
t_{ON}	(s)	Time during which the energizing switch is on
t_{SW}	(s)	Period of a switching signal
TPV		Thermophotovoltaic
V_C	(V)	Voltage across the capacitor C
V_{DD}	(V)	Positive power voltage rail
V_{DS}	(V)	Drain-source voltage across a MOSFET
V_{FB}	(V)	Sensed feedback voltage in the feedback loop
V_{GS}	(V)	Gate-source drive voltage of a MOSFET
$V_{G(M)}$	(V)	Voltage applied to the gate of the MOSFET M
V_{IN}	(V)	Voltage provided at the input of a DC-DC converter
V_L	(V)	Voltage across the inductor L
V_{LOAD}	(V)	Voltage applied to the load

V_{OSC}	(V)	Voltage waveform provided by the oscillator
V_{OUT}	(V)	Voltage provided at the output of a DC-DC converter
V_{REF}	(V)	Reference voltage
V_{TH}	(V)	Threshold voltage of a MOSFET
Z_{LOAD}	(Ω)	Impedance of the load connected to the load side

Subscripts and superscripts

c	Cold
h	Hot
i	Inlet
l	Low
m	Mean
max	Maximum
min	Minimum
n	n-type thermo-electric material
o	Ambient state, Outlet

p p-type thermo-electric material

Chapter 1 Introduction

Thermoelectric semiconductor components, which are physically and electrically sturdy solid state devices, are used to convert thermal energy into electrical energy and vice versa. Thermoelectric devices consist of p-type and n-type semiconductor materials which are connected in series electrically by copper conductors and in parallel thermally by applied ceramic layers on both sides of TE module. In addition to power generation, thermoelectric modules can operate as heat pumping device for both cooling and heating applications. This project will focus on the power generation mode. In this mode, thermoelectric power generator produces an electrical potential across its terminals within the applied temperature difference between hot and cold surfaces of TE module because of the Seebeck effect. To convert this produced electrical potential into useful energy, a load is applied into the system and the current begins to flow through the module. This current flow generates heat due to Joule heating. The generated heat is transmitted from the hot side to the cold side due to the Peltier effect which causes power loss in the system.

The thermoelectric modules which are commercially available vary in thickness and area which determine TE module characteristics. Internal resistance, current, voltage and power output values are related to the cross-sectional area of the TE legs. In TE modules of the same size, a different number of couples can be placed by adjusting the cross-sectional area in order to obtain a different current voltage rating. In addition to area adjustment, varied ratings can be achieved by connecting modules in parallel or series.

A thermoelectric power generator unit has several advantages over other power generation implementations due to its non-moving components, sturdy and reliable features and it can be adapted into many applications with ease as all it requires is a temperature gradient between its surfaces. Recent research of TE power generation shows that there is an increasing interest into waste heat recovery systems, which are varied from automotive to industrial plants TEG applications. In addition to waste heat recovery, another area of interest in TEG applications is photovoltaic and TEG cascade systems which are mentioned in the literature review.

A thermoelectric generator module is represented by a voltage source and an internal resistor which are varied corresponding to the temperature gradient. In both steady state and transient conditions, the amount of power transmitted to the load alters corresponding to the load resistor value. To provide maximum power transmission the load resistor value should match the internal resistance value of the generator. The best way to obtain this match is to apply a maximum power point tracking system to the complete system.

TE generator units generally operate in the transient mode due to the implementation of thermally variant systems and current software tools are not capable of providing accurate simulation data of both thermal and electrical cascaded systems, especially in variable operating points which occur due to a change in the load side or heat source. In these situations, current software tools become incompatible. During the implementation of an actual test rig, accurate

transient performance simulation data will have a significant role to play in being able to achieve successful results from the generator.

Chapter 3 initially introduces a novel mathematical equation of heat transfer which takes ambient temperature as a variable parameter. In addition to variable ambient temperature, most of the parameters of thermoelectric phenomena, applied into the heat transfer equation, are converted into temperature dependant parameters, therefore the accuracy of the simulation data is increased significantly. Secondly, this novel heat transfer equation is applied into a system in two dimensions, contrary to most of the researcher`s one dimensional simulations, further enhancing the accuracy of the simulation results and improving the equation. This simulation program is created in MATLAB and the experimental and simulation data comparison is presented.

Chapter 5 presents a power output simulation of a large scale TE generator which consists of 40 TE modules. In the power output simulation, most of the parameters are applied as temperature dependant, as in the heat transfer simulation program, to increase efficiency. The designed program initiates computation of a single TE pellet`s 20 nodes and can reach up to 40 TE modules in total, recording both the electrical outputs and thermal inputs. In addition to large scale generator unit design, the heat source is also converted into a dynamic exhaust gas source within the NEDC driving cycle by using ADVISOR software program. In this program, MATLAB and Simulink software programs are combined to provide transient performance in an electrical circuit, the MATLAB

programs provide the electrical parameters while Simulink operates the power output and applies it into the H-Bridge converter.

In addition to the simulations, chapter 6 introduces a H-Bridge DC-DC converter design and installation which enhances the power transfer significantly over direct connections between the generator and the load. Chapter 6 also introduces the maximum power point tracking methods applied to a power converter to increase the efficiency of the overall system.

1.1 Thesis structure

The following is a brief description of each of the chapters forming this thesis:

Chapter 2 investigates current implementations of thermoelectric generators and introduces a literature review corresponding to the topics examined in this thesis.

Chapter 3 introduces the principles of thermoelectric generation in order to establish an understanding of thermal to electrical energy conversion. A novel Heat transfer equation and analysis through an innovative two dimensional heat transfer simulation of a single TE couple is also presented.

Chapter 4 introduces DC-DC power conversion principles and a mathematical analysis of various conversion methods. Comparison and conversion ratios of power converters is represented.

Chapter 5 presents a simulation of a large scale thermoelectric power generator unit which provides data of thermal input and electrical output data. A H-Bridge DC-DC converter simulation, which is connected to a large scale thermoelectric

power generator unit, is compared with other methods and components and the results are presented in this chapter.

Chapter 6 proposes a H-Bridge DC-DC Converter design which is presented within the analysis of dead time and converter output data. The designed online perturb and observe maximum power point tracking (MPPT) system and offline incremental conductance MPPT system is presented.

Chapter 7 introduces the designs of 4 test rigs which are built as a single TE module, 16 TE modules and half scale and full scale TE generators. The experimental data, obstacles and achievements of these test rigs are represented in this chapter. The designed data acquisition unit and dynamic data monitoring program is also represented. Analysis of the future development of the four test rigs is also outlined in this chapter.

1.2 Original contribution

- Novel heat transfer equation and analysis (Chapter 3).
- Innovative 2-D heat transfer simulation program of single TE couple (Chapter 3).
- Innovative large scale dynamic TE generator simulation program (Chapter 5).
- Dead time analysis of H-Bridge DC-DC converter (Chapter 6).
- Power converter duty cycle effect analysis (Chapter 6).
- Maximum power point tracking system (Chapter 6).

- Data acquisition unit design (Chapter 7).
- Dynamic data monitoring program (Chapter 7).
- Test rigs design and installations (Chapter 7).

Chapter 2 Literature Review

2.1 Background of thermoelectric devices

Thermoelectric modules can operate in three separate modes which are power generator, coolant and heat source. The power generator mode is implemented by applying a temperature difference between the two sides of the module which then converts heat energy into electrical energy. The coolant and heating modes work by applying a potential difference across the thermoelectric module, according to the current direction, the TE module transfers heat from one side to the other side. Thus the required hot or cold side of the TE is applied to system corresponding to the desired application or mode, in addition all of the modes operate with direct current (DC). Main thermoelectric topology is essential to comprehend the characteristics of the thermoelectric components and it is explained in detail by Bergman, T. L. et al. [1], while comprehensively demonstration of the materials, phenomena and applications of thermoelectric topologies published by Veljko Zlatic and Alexander Hewson [2], [3].

Former applications of TE generators are limited to military, space and medical usage because of their high durability, high expense and nominal efficiency. Due to improvements of the materials and decreases in cost, the thermoelectric generator and refrigerator have been used in instruments and industrial or commercial products, as power generation or cooling devices for specific purposes [4]. The power generator application of thermoelectric components generally alludes to TEGs, which is the application method that has been implemented in this thesis.

Thermoelectric power generators are used in space and automotive applications, such as radioisotope thermoelectric generators, which have been successfully used to power a number of space missions, including the Apollo lunar missions, the Viking Mars landers, Pioneer 10 and 11, and the Voyager, Ulysses, Galileo, and Cassini outer-planet space crafts. The configuration of a general-purpose heat source radioisotope thermoelectric generator (GPHS-RTG), used on the Galileo, Ulysses, and Cassini space crafts, provides years of continuous electric power and is designed to operate in the vacuum of space. It uses 18 GPHS modules with a total nominal thermal power of 4500 W and the specific power of the generator is about 5.1 W/kg, nearly four times that of the first RTGs flown [5].

Due to energy expenses and environmental issues, the investigation of renewable energy and waste energy recovery systems to produce power has increased in popularity. TE modules applied into waste energy recovery system are becoming widely implemented corresponding to the development of materials. The enhancement of high efficient TE components, advanced materials and implementations are commented in detail by Biswas et al [6]. A cost-wise examination of thermoelectric power generators for automotive is investigated by Hendricks, T. et al. [7].

2.2 Applications of thermoelectric power generators

Waste heat recovery systems, which convert heat power into electrical power through the use of a TE generator in an exhaust system, are a research area of

increasing interest. TE materials for automotive TEG applications must have good intrinsic performance, be thermomechanically compatible, and be chemically stable in the 400 K to 850 K temperature range [8]. One of the main projects of TEG automotive implementations is overseen by BMW and FORD, the results of this project are illustrated by Crane et al. [9]. Two TEGs have been successfully integrated and tested on a BMW X6 and Lincoln MKT with over 600 W of power produced in vehicle tests and over 700 W produced in bench tests [9]. According to the results of BMW, in a thermoelectric power generator, the current output reaches high values up, to 800 A, while the maximum voltage output is 1.75 V. This high current causes difficulties in the battery charging areas [9]. Another project, operated by General Motors, is implemented by using 42 Bi₂TE₃ thermoelectric module and the results show that the maximum power generation is 33 W, presented by Meisner [10]. Wojciechowski et al. [11] published results of a thermoelectric generator (TEG) mounted on a self-ignition engine (1.3 dm³) and the maximum electrical power generated by the constructed prototype TEG generator is 88 W for the assumed SIE engine load parameters (1600 rpm, 8 kW). Frobenius et al. [12] demonstrate that the measured power is 150 W at an exhaust gas mass flow of 180 kg/h while the expected power output is 160 W according to the design calculations.

Bismuth telluride is the most applied thermoelectric material in TE power generators, however this material has a 350°C maximum temperature limitation. Due to this limitation, higher temperature operating materials are another research area that can improve overall efficiency. Skutterudites, Clathrates, Complex Chalcogenides, Oxides and Half-Heusler Alloys are investigated by

Zhang et al. [13]. Although the efficiencies of these materials are higher than Bi_2Te_3 , they are difficult to apply into actual systems because they are chemically reactive, difficult to create electrical connections with and expensive [14]. In addition to bulk materials, nanostructured materials are also examined and improvements of figure of merit (ZT) values are analysed. Mehta et al. [25] indicate that the highest room-temperature ZT that has been obtained is 1.1 for bulk nanostructured pellets of a single-component n-type Bi_2Te_3 and multicomponent p-type $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}$ pellets obtained from a $25:75\text{Bi}_2\text{Te}_3:\text{Sb}_2\text{Te}_3$ mixture of nanoplates.

Some of the TEG systems are implemented by using a stove as the heat source. The TE generator which is designed by Champier et al. [15] produces a maximum electrical power of 9.5 W and therefore the obtainable maximum power is 7.6 W because of losses in the electronic converter. Rinalde et al. [16] showed that a stove TEG can reach a maximum power of 12.3 W, for a temperature gap of 200 °C, which is still 35% below the one claimed by the manufacturer (19 W). In O'Shaughnessy et al. [17] a TE generator implemented into five stoves is capable of producing up to 9 W h therefore 8 W h of power can be stored in a battery.

Thermoelectric power generators are installed into combined heat and power (CHP) plants at different locations and have been investigated by Chen et al. [18]. A theoretical TE generator application of geothermal energy recovery estimates a 1kW power generation at 200 K [19]. Recently, combining a thermoelectric generator with a photovoltaic (PV) power generator has been of

increased interest. A novel DSSC/SSA/TE combination, which was designed by Wang et al. [20], provides an improvement in efficiency from 9.26% to 13.8%. Under the consideration of annual power production, a comparison by Sark [21] indicates that The PV module deployed in Malaga would yield an annual amount of energy of 211.9 kW h. The TE converter would add an additional 31.1 kW h thus totalling 243.0 kW h. Another comparison of PV and TE applications is performed by Yang and Yin [22], in this comparison three scenarios are investigated, a lone PV unit, a PV/water tube combination and a PV/TE/water tube combination. The results indicate that the third scenario improved efficiency from 12.6% to 16% compared to the first scenario, which is a lone PV unit, but the authors obtained a 16.6% efficiency in the second scenario. The authors mentioned that the efficiency of the third scenario, the PV/TE/Water Tube combination, can be improved by using an enhanced TE material, that is a TE material with a higher efficiency. A Cascaded TPV and TE power generation system which operates by taking residual heat from the TPV and applying it to the input of the TE converter is proposed by Qiu and Haiden [23] and a 306 W power production is achieved with 5.2% efficiency. Comprehensive investigations are carried out by Zebarjadi et al. [24], with the analysis within this article based on three parts; advances in studying carrier transport in thermoelectric materials, new strategies for designing high-efficiency and low-cost thermoelectric materials and new applications of TE devices, especially solar thermoelectric power generators (STEGs).

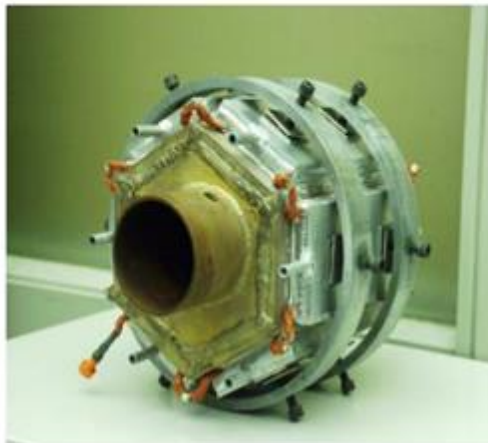
In light of the above literature reviews, it appears that the disadvantage of low heat energy to electrical power conversion can be eliminated by improving the

produced power in waste heat recovery applications and within this improvement the cost per Watt can be decreased and TEG systems can become competitive financially.

2.2.1 TE generator implementations in the automotive industry

Before cylindrical thermoelectric generators thermocouple modules were implemented into rectangular, octagonal and hexagonal shapes as we can see in Fig. 2.1.a.

Gen I – GM R&D (1996)



GenII-GMR&D(2006)



Figure 2-1.a) Hexagonal TEG (109W) [70] Figure 2.1.b) Cylindrical TEG (290W) [70]

In these shapes, the hot sides of the generators are directly facing the exhaust pipes, this direct interaction causes a reduction in heat absorption from the thermoelectric module and a low operating temperature. For this reason, the BiTe material used in thermoelectric modules are chosen for this type of application. In Fig. 2.1.b, a cylindrical type of thermoelectric generator is

implemented, but the heat sink is placed between the hot side of module and the exhaust pipe to increase absorbed heat and temperature difference, in order to obtain a higher efficiency than previous applications.

Another difference is between Fig. 2.1.a type of generators and Fig. 2.1.b type of generators is the cooling system. In Fig. 2.1.a, a cooling liquid is delivered to the modules individually but in Fig. 2.1.b the cooling liquid is using one inlet and one outlet to accomplish its cooling operation which provides higher cooling efficiency over previous generator systems.



Figure 2-2 Bi₂Te₃ TEG(2007) and High Temperature TEG, P_{max}=300W (2009).

[71]

After their 300W thermoelectric generator, which is shown in Fig. 2.2, BMW placed a generator at a higher temperature point in the exhaust pipe and changed the TE element to fulfil the requirements. This implementation consists of an

EGR cooling section and a TEG section which is shown in Fig 2.3. Also, the structure of the generator unit is shown in Fig 2.4. In this application, the BiTe thermoelectric material is replaced by PbTe and achieves around 900W of power production, is observed at full load in a 3.4L automotive, which is a significant improvement on the previous BMW TEGs.



Figure 2-3 BMW PbTe TE generator. [71]



Figure 2-4 BMW PbTe TEG section structure. [71]

2.3 Thermoelectric materials

2.3.1 Seebeck and Peltier Effects

A discussion of thermoelectric components and effects should begin with the most elementary phenomena, the Seebeck coefficient (Thermo-power). In the 1800s, Seebeck noticed that when two different elements were combined together and their connections had a difference in temperatures (T and $T \pm \Delta T$), then a difference in voltage (ΔV) corresponding to the difference in temperature (ΔT) developed.

The change in voltage is proportional to the difference of temperature ($\Delta V/\Delta T$) is linked to a fundamental structure of the component, described the Seebeck coefficient (α). Building a temperature difference across a component might help to understand Seebeck effect; before the electric field is built high enough to block the subsequent electron flow, the more active electrons shift to a lower potential energy.

When we compare the Seebeck coefficient values of metals and semiconductor, we observe that they are very small for metals and very high for semiconductors, values are respectively few microvolts per degree Kelvin to few hundred microvolts per degree Kelvin. After the discovery of the Seebeck effect, Peltier found out a similar effect (Peltier effect): Heat absorption or rejection at the connection is determined by the direction of the current when the current is going through the connection of two different elements.

The Peltier effect occurs mostly due to the difference in the Fermi energies of the two components. The Peltier and Seebeck effects are linked with each other, as displayed in the description of the Peltier effect formula, $\Pi = \alpha T$.

The ratio of rejected or absorbed heat at the connection is shown by $\dot{Q} = \alpha IT$, where I is the current along the connection and T is temperature in Kelvin.

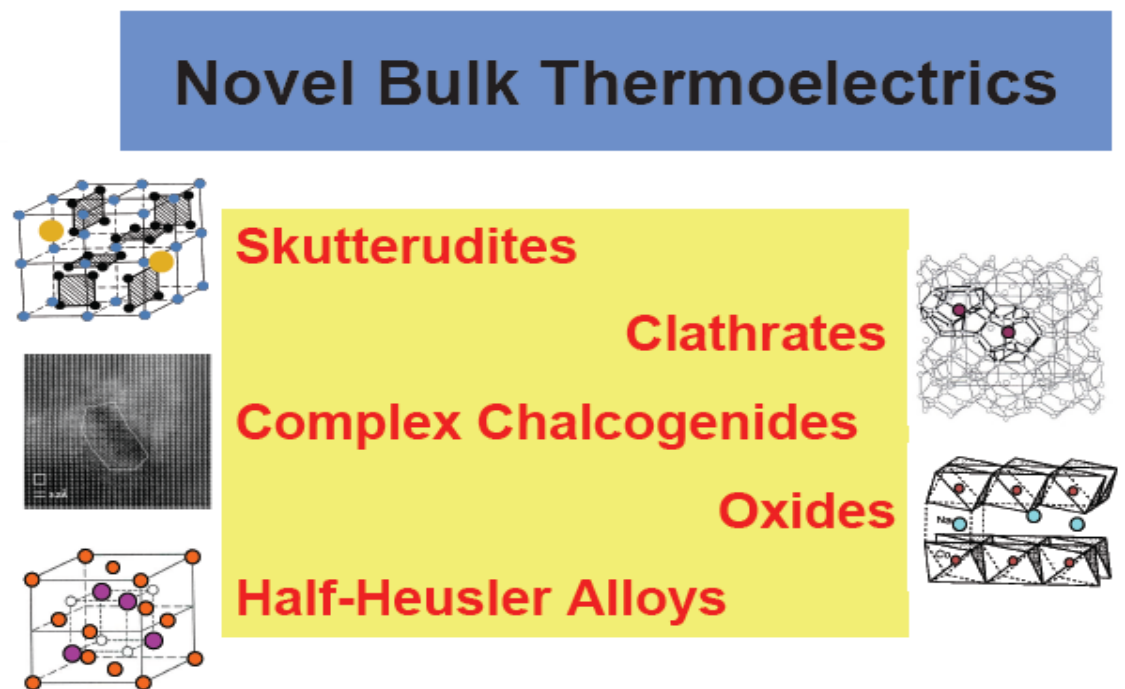


Figure 2-5 Open crystalline environment Nanometer-size structural features. [70]

There are several types of thermoelectric materials available, but these five types of thermoelectric materials, shown in Fig 2.5, are most commonly used in thermoelectric generator applications. For instance, the Half-Heusler alloy is used with Bi_2Te_3 in Bosch automotive TEG application [79], the complex chalcogenide is used in BMW ATEG application. The most important distinctive fact of the thermoelectric materials is figure of merit (zT), with the appropriate

elements for our automotive TEG application listed with their zT values and operating temperatures below:

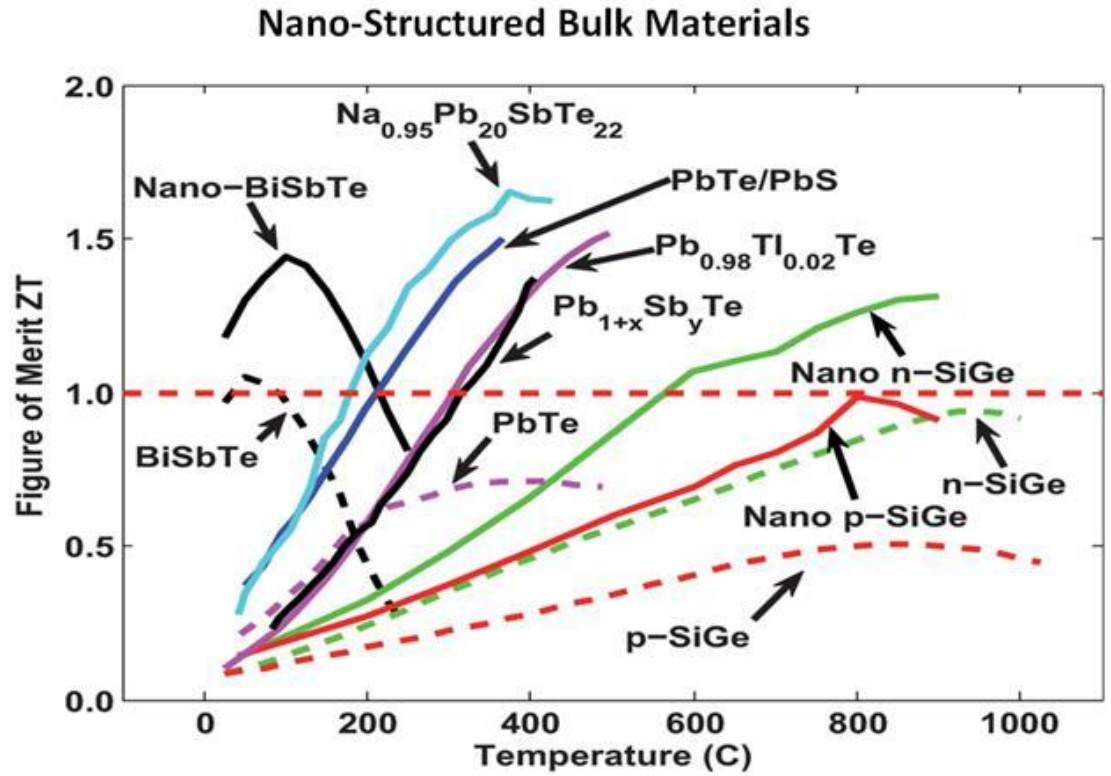


Figure 2-6 Figure of merit ZT of current state of the art thermoelectric materials versus temperature. [69]

The dashed lines show the maximum ZT values for the bulk state of the art materials, and the solid lines show some recently reported ZT values, many of which were obtained in bulk nanostructured materials. (BiSbTe [72], Na_{0.95}Pb₂₀SbTe₂₂ [73], PbTe/PbS [74] Pb_{0.98}Tl_{0.02}Te [75] Pb_{1+x}Sb_yTe [76] n-SiGe [77]; p-SiGe [78]).

2.4 Simulation of thermoelectric modules

An accurate simulation of the TE generator, module and even the thermoelectric couple is significant and essential for the overall success of the project, as the comparison between the simulated and actual data provides an understanding of unexpected losses in implementations due to their unpredictable structures. As seen in several research studies, even for the same components researchers sometimes obtained different values when testing materials. This can be due to problems with uniformly heating the surface and many other reasons. Consequently, calculation and simulation of TE generators are necessary due to the material's dynamic characteristics, which vary at different temperatures.

Calculations of thermoelectric effects at steady state conditions and material characteristics are illustrated in [1], [2] and [3]. The electro-thermo equivalent circuit model of a TEG is constructed by Shiho Kim [26] considering the electric circuit models of thermal behaviours which are the equivalent source model of a TEG with an internal temperature difference and the Thevenin equivalent source model of a TEG with an external temperature difference.

A similar design to General Motors' TEG unit is simulated by Kumar et al. [27], where steady-state analysis of hot exhaust gas flowing along the TEG length is performed under the construction of a rectangular configuration of a TEG where TE modules are placed on the top and the bottom surface. One of the main mistakes has been indicated by Fraisse et al. [28] as when the Seebeck coefficient is taken as a constant, inherently the Thomson coefficient becomes zero. For any model, the Thomson coefficient needs to be neglected when the Seebeck

coefficient is taken constant because of this neglecting, the analytical model becomes less accurate.

Another simulation is implemented by Shen et al. [29]. This simulation can be considered to differ from the others because it was designed to choose suitable TEM for actual application requirements and the parameters are plotted according to their thermal resistance. A thermoelectric power generator for an automotive application is simulated by Wang et al. [30]. In this simulation, the comparison of air and water cooling is examined and it indicated that air cooling has a lower efficiency than water cooling. Al-Merbati et al. [31] simulated a trapezoidal pin thermoelectric power generator which differs from commercial TE couples. They also simulated the thermal stress of a TE couple in addition to the thermal efficiency of a TE couple and an improvement of the thermal stress is illustrated.

The electrical dynamic response is illustrated by [32] which indicates that rapid response takes place in the system therefore energy conversion builds up immediately, in actual applications however, this condition does not affect the thermal dynamics because they are operated by thermal elements. Parallel connected electrical capacitance stores the heat energy, therefore a thermal model is converted into an electrical model. In addition, variance in the stored energy in reference to a time related term is simulated by Chen M. et al. [33].

Most of the simulations are realised by creating equivalent circuits which consist of resistances and capacitances corresponding to Joule heating, heat conduction, Peltier, Seebeck and the Thomson effect with the rest of the parts considered as

thermal impedances. However, a more accurate simulation can be achieved by applying physical equations, which contain the material characteristics, as is demonstrated in this thesis. Another example of a thermoelectric simulation according to physical equations is illustrated by Alata et al. [34].

In addition to TE power generator simulations, a transient thermoelectric cooler simulation is also illustrated by Meng et al. [35]. The examined literature constructed a basic methodology for a single thermocouple simulation, thermoelectric module and thermoelectric generator, which is illustrated in section 4, and the missing aspects of the literature are observed and applied into the simulation. In addition, a two-dimensional simulation is achieved instead of a one-dimensional simulation, contrary to most of the previous research studies, to increase accuracy of the results.

2.5 Enhancement power generation at TEGs

Thermoelectric generators for automotive applications are considered as dynamic systems which have altering temperature values on the heat source side, thus it is important to carry the current power condition to the maximum power condition rapidly and accurately to increase the efficiency of the system. DC-DC power converters regulate the TE generator's output voltage with the maximum power point method to obtain the same internal resistance value of the TEG in the converters input side. This operation can be achieved by adjusting the duty cycle which creates and applies a virtual resistor load to the TEG.

MPP tracking can be achieved through several methods according to system requirements. Thus, these methodologies have been proposed in the literature [36], [37], [38], [39], [40], [41] and [42]. Fixed duty cycle, Beta method, Hill climbing/perturb and observe (P&O), P&O Based on PI, Incremental conductance, Constant voltage and current, Fractional open-circuit voltage (FOC), Modified open-circuit voltage method, Pilot cell, Fractional short-circuit current and Parasitic capacitance/dc-link capacitor droop control are some of the MPPT methods which are investigated and compared by de Brito et al. [39] and Eltawil, M., & Zhao, Z [43].

A commonly implemented maximum power point tracking algorithm in literature is the perturb and observe method for thermoelectric power generation applications. In this method, a comparison of current and previous power measurements leads to a conversion. In this comparison, a controller reacts, which refers to the perturb aspect, then the output power is measured again, which refers to the observe aspect. As reported by Vieira and Mota [44], two scenarios are compared. In the first scenario, the TEG is connected to a battery without a converter and in the second scenario, the TEG is connected to a battery via converter which is controlled by the P&O MPPT methodology., This comparison shows that a 34% increase in efficiency is obtained with the implementation of the converter. However, this 34% efficiency increase cannot be assumed to have been obtained due to the MPPT method or the converter because this comparison does not provide information about the TEG battery connection via the converter without the MPPT. The perturb and observe method is implemented by Champier et al. [44] and they reported a 99% efficiency in

power conversion. Another common MPPT method is incremental conductance topology, which can follow a change in the supply side better than P&O, however it requires more computations in the controller. This method is implemented for a TEG by Kim et al. [45] and it is shown that a 95% conversion efficiency is observed within the boost converter.

A comparison of the perturb and observe method and the extremum seeking method (ESC) is illustrated by Phillip et al. [46]. It is observed that the ESC method has a higher efficiency than the P&O method, however this method adds complexity into the system, thus the low efficiency difference P&O method can be a better choice than ESC in actual implementations.

Another MPPT method, fractional open circuit, is suitable for low cost and low power applications. This method requires a sample of a supply short circuit current or an open voltage, therefore the supply disconnects from the load during this sampling time. In addition, if the sampling period is kept long, it can cause power loss in the system due to operating in a previous maximum power point. The advantages of this method are the cost and the simplicity of circuit and control system. Ahmad [47] implemented a fractional open circuit method with a $2\mu\text{s}$ disconnection between supply and load to overcome power losses. Cho et al. [48] applied an FOC method into a TEG conversion and claimed that the observed efficiency is more than 98% which is higher than P&O and IC methods. TEG conversion with FOC method is proposed in literature [38], [49] and [50] and stated that the observed efficiency is better than P&O.

Chapter 3 Methodology of Thermoelectric Generation

3.1 Thermoelectric Generation

3.1.1 Thermoelectric Generation Principles

A TEG is an immobile DC power supply which has no moving components. The TE component's parameters are temperature dependant in other words they are a function of temperature. For this reason, thermoelectric module construction and energy conversion topology are demonstrated over a single thermoelectric couple as shown in Figure 3.1. A thermoelectric couple is made of p-type and n-type semiconductors, the p-type component provides a positive Seebeck coefficient and the n-type component provides a negative Seebeck coefficient. Despite of the fact that the p and n thermoelectric couples are placed in parallel for thermal heat transfer, they are connected in series with each other electrically.

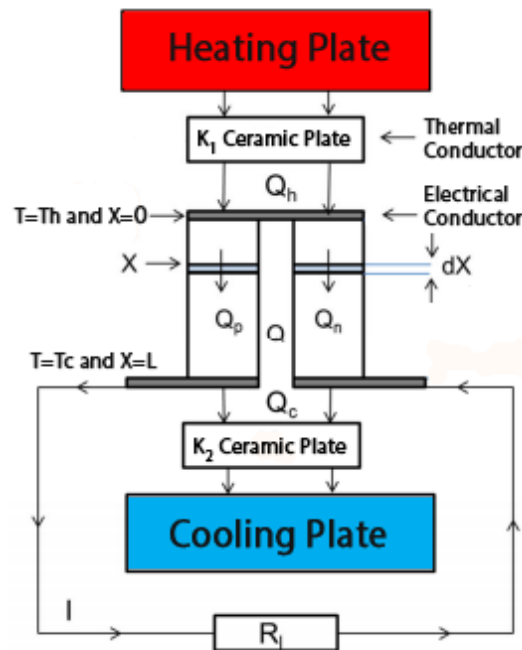


Figure 3-1 Thermoelectric module.

The thermoelectric effect occurs at a junction of two different conductors, where either a temperature variance is generated by an electric field potential or an electric potential difference is generated by a temperature variance, which is caused by the thermoelectric effect. A thermoelectric component's characteristic structure is based on three thermoelectric phenomena, the Seebeck effect, which generates current due to a temperature difference, the Peltier effect, which produces heat due to a current and the Thomson effect, which refers to conductor heating and cooling. Internal and external power losses occur in a TEG like in any other power generator and they reduce the performance of TE generator. Inner losses occur due to conduction heat losses ($K (T_h - T_c)$) across the junctions and resistive losses ($I^2 R$). Outer losses occur during heat transfer at the heat exchange unit. Inner losses of thermoelectric component are demonstrated as follows.

The generation of electrical potential due to the Seebeck effect is obtained by supplying a temperature variance between the hot side and the cold side of the TE component and the open circuit voltage (dV) is illustrated by [80]:

$$dV = \alpha_{p,n} dT \quad (3-1)$$

where, dT is the temperature variance between the terminals of the TE component and $\alpha_{p,n}$ is the Seebeck coefficient across the TE couple.

The Peltier effect refers to a heat transfer rate (Q) across the terminals of the TE and it is illustrated by [51]:

$$Q = \Pi_{p,n} I \quad (3-2)$$

where, $\Pi_{p,n}$ is the Peltier coefficient and I is the current.

The Thomson coefficient $\tau_{p,n}$ determines the produced or absorbed heat according to a temperature variance which is caused by current flow [80].

$$Q = \tau_{p,n} I \frac{dT}{dx} \quad (3-3)$$

The P-type thermoelectric component performance is determined by the one directional energy conversion topology within the length of dx , in accordance with an estimation of ideal conditions which lead to the equalisation of heat energy and electrical power ($Q=P$).

$$dQ_p = Q_p(x + dx) - Q_p(x) = I^2 dr_p \quad (3-4)$$

where, r_p is the inner resistance across dx is calculated as following:

$$dr_p = \frac{\rho_p}{A_p} dx \quad (3-5)$$

where, ρ_p is the electrical resistivity of p-leg and A_p is the cross sectional area of p-leg. After combination and integration of Eq. (3-4) and Eq. (3-5), the following calculations are illustrated:

$$\int_0^x Q_p(x + dx) - Q_p(x) = \int_0^x I^2 \frac{\rho_p}{A_p} dx \quad (3-6)$$

$$I^2 \frac{\rho_p}{A_p} x - Q_p(x) + C_1 = 0 \quad (3-7)$$

The heat transfer of the p-type leg by conduction can be demonstrated as follows [93]:

$$Q_p(x) = -k_p A_p \frac{dT_p(x)}{dx} \quad (3-8)$$

The gradient of the p-type leg temperature is described as $\frac{dT_p(x)}{dx}$ and k_p is the TE thermal conductivity. Combining Eq. (3-7) and Eq. (3-8), yields:

$$I^2 \frac{\rho_p}{A_p} x + k_p A_p \frac{dT_p(x)}{dx} + C_1 = 0 \quad (3-9)$$

Integrating Eq. (3.9) with respect to x;

$$I^2 \frac{\rho_p}{A_p} \frac{x^2}{2} + k_p A_p T_p(x) + C_1 x + C_2 = 0 \quad (3-10)$$

The constant values (C_1, C_2) are applied into the equation after integration and are defined by the boundary conditions, which are the hot surface and the cold surface temperatures. C_2 is calculated when $x=0$ ($T_p(0) = T_h$) and C_1 is calculated when $x=L$ ($T_p(L) = T_c$):

$$C_2 = -k_p A_p T_h \quad (3-11)$$

$$C_1 = k_p A_p \frac{(T_h - T_c)}{L} - \frac{I^2 \rho_p L}{A_p} \quad (3-12)$$

When x is determined with length of the leg (L), thermal conductance (K_p) and internal resistance (R_p) of p-type leg can be determined as:

$$R_p = \frac{\rho_p L}{A_p} \text{ and } K_p = \frac{k_p A_p}{L}$$

$Q_p(0)$ and $Q_p(L)$ are derived from Eq (3.7):

$$Q_p(0) = K_p(T_h - T_c) - \frac{1}{2}I^2R_p \quad (3-13)$$

$$Q_p(L) = Q_p(0) + I^2R_p = K_p(T_h - T_c) + \frac{1}{2}I^2R_p \quad (3-14)$$

The N-type leg equations of $Q_n(0)$ and $Q_n(L)$ are derived by using same procedure:

$$Q_n(0) = K_n(T_h - T_c) - \frac{1}{2}I^2R_n \quad (3-15)$$

$$Q_n(L) = K_n(T_h - T_c) + \frac{1}{2}I^2R_n \quad (3-16)$$

The thermoelectric couple energy conversion equations are derived as:

$$Q(0) = K(T_h - T_c) - \frac{1}{2}I^2R \quad (3-17)$$

$$Q(L) = K(T_h - T_c) + \frac{1}{2}I^2R \quad (3-18)$$

where, $K = K_p + K_n$ and $R = R_p + R_n$

The Peltier effect refers to the absorption of heat by the thermoelectric component, therefore the hot side energy conversion is derived by:

$$Q_h = \alpha T_h I + Q(0) \quad (3-19)$$

In the same way, the Peltier effect refers to a heat rejection by the thermoelectric component therefore cold side energy conversion is derived by:

$$Q_c = \alpha T_c I + Q(L) \quad (3-20)$$

where, α is the Seebeck coefficient across the p-type and n-type legs, α is derived by:

$$\alpha = \alpha_p - \alpha_n \quad (3-21)$$

The heat input and rejected heat formula can be adopted as follow:

$$Q_h = \alpha T_h I + K(T_h - T_c) - \frac{1}{2} I^2 R \quad (3-22)$$

$$Q_c = \alpha T_c I + K(T_h - T_c) + \frac{1}{2} I^2 R \quad (3-23)$$

In accordance with the assumption of ideal conditions, the power output is calculated using the difference in the hot side and cold side heat transfer.

$$P_{out} = Q_h - Q_c \quad (3-24)$$

$$P_{out} = \alpha I(T_h - T_c) - I^2 R \quad (3-25)$$

The efficiency of the thermoelectric component is determined as:

$$\eta = \frac{Q_h - Q_c}{Q_h} = \frac{P_{out}}{Q_h} = \frac{\alpha I(T_h - T_c) - I^2 R}{\alpha T_h I + K(T_h - T_c) - \frac{1}{2} I^2 R} \quad (3-26)$$

Maximum power output is achieved by equalising the load resistance and the internal resistance and it can be calculated as follow:

$$R = R_{load} \quad V = I(R + R_{load}) \quad V = \alpha \Delta T$$

$$P_{max} = \frac{V^2}{4R_{load}} = \frac{(\alpha \Delta T)^2}{4R_{load}} = I^2 R_{load} \quad (3-27)$$

Within the assumptions of $\rho = \rho_n = \rho_p$, $l = l_n = l_p$ and $A = A_n = A_p$;

where, $R = \rho \frac{l}{A}$, P_{max} is determined as:

$$P_{max} = \frac{(\alpha\Delta T)^2 A}{4\rho l} = \frac{\alpha}{\rho} \left(\frac{\Delta T}{2}\right)^2 \frac{A}{l} \quad (3-28)$$

The maximum power output calculations lead to factors that determine the increase of P_{out} . These factors are the cross sectional area (A) and the length of the leg (l), P_{max} can be enhanced by an increase of A and a decrease of l .

The characterisation of the TE efficiency is determined by a figure of merit (Z) and is shown to be [92]:

$$Z = \frac{\alpha^2}{RK} \quad (3-29)$$

The maximum thermoelectric device efficiency is derived where the differential of Eq. (3-26) is equal to zero, which is similar to the maximum power calculation.

$$R_{load} = R(\sqrt{1 + ZT_{avg}}) \text{ at } \eta_{max}$$

where, $R_{load} = R_l, V = I(R_{load} + R), T_{avg} = (T_h + T_c)/2$.

$$P = I^2 R_{load} = \left(\frac{V}{R + R_l}\right)^2 R_l = \frac{(\alpha\Delta T)^2 R_l}{(R + R_l)^2} = \frac{(\alpha\Delta T)^2 R_l}{(R + R_l)^2} \frac{1/R}{1/R} = \frac{(\alpha\Delta T)^2 R_l/R}{(1 + R_l/R)^2 R} \quad (3-30)$$

$$P \text{ at } \eta_{max} \text{ is } P = \frac{(\alpha\Delta T)^2 \sqrt{1 + ZT_{avg}}}{(1 + \sqrt{1 + ZT_{avg}})^2 R} \quad (3-31)$$

$$\eta_{max} = \left(\frac{\sqrt{1 + ZT_{avg}} - 1}{\sqrt{1 + ZT_{avg}} + \frac{T_c}{T_h}}\right) \frac{T_h - T_c}{T_h} = \phi \eta_{carnot} \quad (3-32)$$

Within the assumptions of zero Fourier heat conduction and Ohmic heat loss in the Eq. (3-26). Where, $I^2 R = 0$ and $K(T_h - T_c) = 0$.

$$\eta = \frac{\alpha I(T_h - T_c)}{\alpha T_h I} = \frac{(T_h - T_c)}{T_h} \quad (3-33)$$

The thermoelectric generator efficiency depends on three sections of the system. These sections are illustrated in the above equations. The first section of the efficiency decrease, which is revealed by a comparison between Eq. (3-26) and Eq. (3-32), is explained with the Carnot efficiency. The efficiency drops as a consequence of Fourier heat conduction and resistive losses, which decrease the power output and counts as internal loss.

The second part of the efficiency reduction depends on the thermoelectric couple specifications. The cross sectional area and length of the semiconductor legs determine the power generation, which is illustrated by Eq. (3-30). Despite the fact that these specifications have a major role in efficiency, the fabrication process and applied component's quality has an effect on performance as well.

The third section of the efficiency drop occurs in both hot and cold heat exchanger units, the thermal conductance and heat capacity cause efficiency loss, which counts as an external loss, in the thermoelectric generator. This efficiency dependency is also one of the main factors in determining TEG performance.

In addition to these factors, another obstacle in TE generator design is the fluctuating temperature of the heat supply and cooling system over both sides of the TEM. As an example, a simplified automobile TE generator design is illustrated in Fig 3.2, the heating plate temperatures alter through the inlet to outlet.

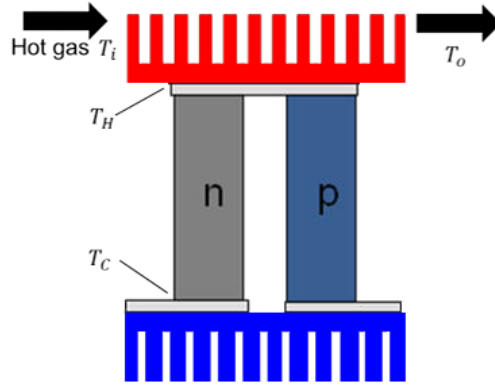


Figure 3-2 Simplified TEG design.

The outlet temperature of the thermoelectric power generator must be greater than T_{hot} or equal to T_{hot} if we consider T_{hot} is constant. Maximum efficiency of conversion under the conditions of constant gas flow is illustrated:

$$\eta = \frac{T_H - T_C}{T_H} \frac{\sqrt{1 + ZT_{avg}} + 1}{\sqrt{1 + ZT_{avg}} + T_C/T_H} \frac{T_i - T_o}{T_i - T_a} = \eta_{max} \frac{T_i - T_o}{T_i - T_a} \quad (3-34)$$

where, T_a is the ambient temperature, T_o is the outlet temperature and T_i is the inlet temperature. $\frac{T_i - T_o}{T_i - T_a}$ determines the heat exchanger effectiveness and under the consideration of $T_h = T_o$, we calculate optimum hot side temperature approximately by:

$$T_H = \sqrt{T_C T_i} \quad (3-35)$$

3.2 Heat Transfer Simulation of a TE Couple

A simulation of the heat transfer on TE generator module is designed in different configurations for greater understanding of every stage. These configurations are

one direction, two direction, steady state condition and transient condition of heat transfer and also n-type and p-type materials are simulated separately. In the simulations, the thermoelectric couple is investigated in nodes, it is divided into 20 nodes (dx) in 1-D heat transfer and 10 nodes at each side in 2-D heat transfer. These simulation's results highlight the reasons for varying the experiments and for more comprehensible results, the heat transfer simulations are designed on a time basis and in two dimensions. A novel part of this simulation is the applied heat transfer formula, which includes an additional loss calculation, which occurs due to ambient temperature variant along TE couple, to obtain a higher accuracy.

3.2.1 One-Dimensional Steady State Heat Transfer

In the one direction simulation, heat transfer from the bottom side to the top side is analysed and time based results show that heat is not transmitting linearly from the hot side to the cold side until the steady state conditions in one direction are reached. Heat transfer graphs demonstrate that the heat shifts in curve shapes are because the hot side of the TE node's temperatures are increasing faster than those of the cold side nodes. As seen in Fig 3.3, the heat transfer graph settles to become linear in the steady state condition. In Fig 3.3, nodes 1 to 20 represent the hot side connection, nodes 20 to 40 symbolize the thermocouple nodes and nodes 40 to 60 represent the cold side connection, which is chosen to be copper in this example.

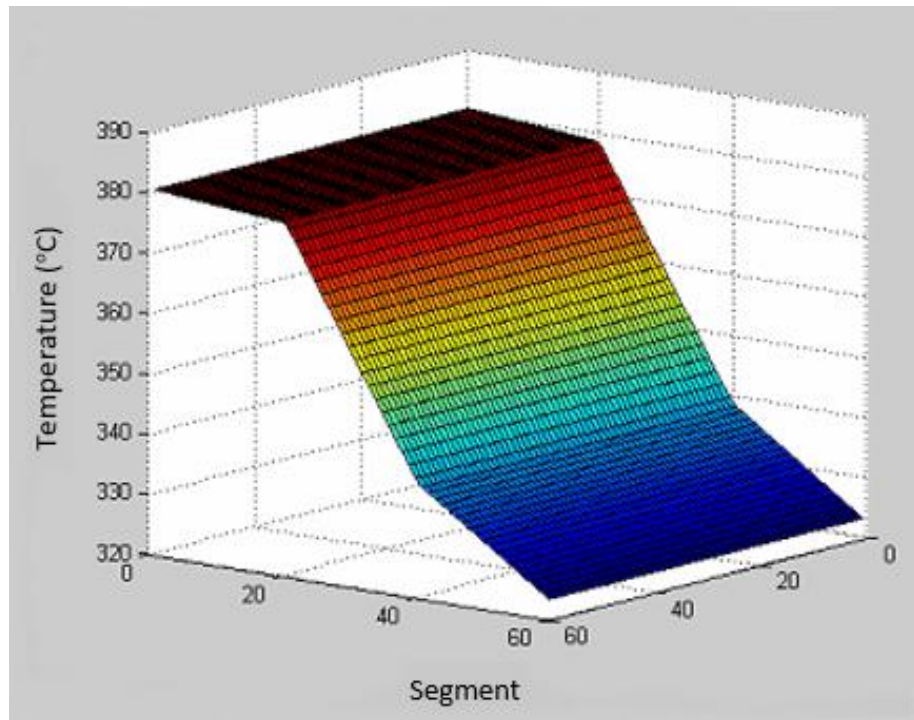


Figure 3-3 Temperature Distributions of Thermoelectric Couple.

The additional nodes that aren't thermocouple nodes are for an understanding of the heat transfer differences on both sides, which we faced in the laboratory experiment. The junction point temperature and the ceramic surface temperature differs by up to 30°C at a 100°C temperature difference between the junctions. In our simulation, the graph displays that there is a 15°C temperature variance between the ceramic surface and the junction point.

This simulation differs from the other heat transfer analysis methods because most of the properties are applied as temperature dependent instead of constant values. The temperature dependent specifications are thermal conductivity (κ), seebeck coefficient (α), electrical conductivity (σ) and internal resistance (R_{in}). All these temperature dependent properties increase the accuracy of the output

values, however it makes the program complex and slows down its solving ability.

The formula applied into the simulation to calculate the heat transfer in one direction is shown in Eq. (3.36). To solve this equation, ode23, the ordinary differential equation solver function, method is used in MATLAB.

$$A \frac{dT}{dx} \left[(\kappa_n + \kappa_p) \frac{dT}{dx} \right] + \frac{I^2}{A} (\rho_n + \rho_p) + I(\tau_n - \tau_p) \frac{dT}{dx} - 2hp \left(T - T_c - \frac{T_h - T_c}{L} x \right) = 0 \quad (3-36)$$

where, ρ is the electrical resistivity, τ is the Thomson coefficient and h is the heat convection coefficient.

3.2.2 Two-Dimensional Steady State Heat Transfer

In the steady state simulation, the thermoelectric couple is examined as n- type and p-type to obtain more succesful results due to the fact that both types have different formulae which to calculate the characteristic specifications of the TE shown in Eq. (3-37) [52], Eq. (3-38) [52] and Eq. (3-39) [52].

Thermal conductivity:

$$\begin{aligned} \kappa_n &= (0.0000334545.T^2 - 0.023350303.T + 5.606333) \frac{W}{mK} \\ \kappa_p &= (0.0000361558.T^2 - 0.026351342.T + 6.22162) \frac{W}{mK} \end{aligned} \quad (3-37)$$

Seebeck Coefficient:

$$\alpha_n = (0.001530736.T^2 - 1.08058874.T - 28.338095) \frac{\mu V}{K}$$

$$\alpha_p = (-0.003638095.T^2 + 2.74380952.T - 296.214286) \frac{\mu V}{K} \quad (3-38)$$

Electrical Conductivity:

$$\sigma_n = (0.015601732.T^2 - 15.708052.T + 4466.38095)10^2 \frac{S}{m}$$

$$\sigma_p = (0.01057143.T^2 - 10.16048.T - 3113.71429).10^2 \frac{S}{m} \quad (3-39)$$

Another difference from the other heat transfer analyses is the main heat distribution formula which is shown in Eq. (3-40). In this formula, ambient temperature is applied into the calculation as a temperature dependent variable instead of constant temperature. Ambient temperature is calculated at every node by considering the current node temperature, the hot side temperature and the cold side temperature to allow the observation of more accurate results. This means that the ambient temperature is a variable and it changes across the thermocouple due to the heat dissipation of the TE pellets.

$$\begin{aligned} & A \frac{d}{dx} \left[(\kappa_n + \kappa_p) \frac{dT}{dx} \right] + \frac{I^2}{A} (\rho_n + \rho_p) + I(\tau_n - \tau_p) \frac{dT}{dx} - 2hp \left(T - T_c - \frac{T_h - T_c}{L} x \right) + \\ & A \frac{d}{dy} \left[(\kappa_n + \kappa_p) \frac{dT}{dy} \right] + \frac{I^2}{A} (\rho_n + \rho_p) + I(\tau_n - \tau_p) \frac{dT}{dy} - 2hp \left(T - T_c - \frac{T_h - T_c}{L} y \right) = \\ & 0 \end{aligned} \quad (3-40)$$

To compare the simulation results with experimental data, the temperature dependent voltage output is analysed in the simulation and the thermoelectric couple's n-type and p-type output voltages are plotted in Fig 3.4.

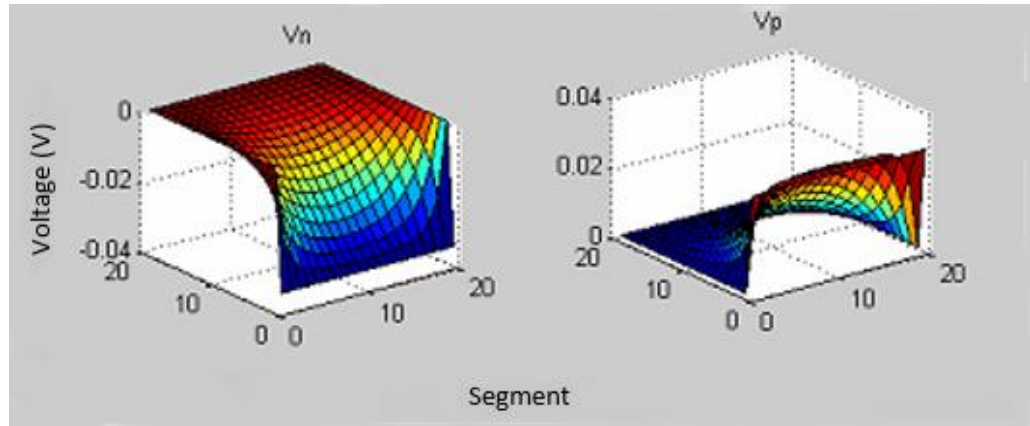


Figure 3-4 Voltage output of the TE couples.

As seen in Fig 3.4, the n-type TE couple voltage output is negative, the reason for the negative output is the direction in which the current moves, it goes from the bottom to the top in the n-type TE couple. In the total voltage output calculation, we consider the potential difference between two points, thus the output voltage is calculated as $V_p - V_n$ which gives us positive output values and is shown in Fig 3.5.

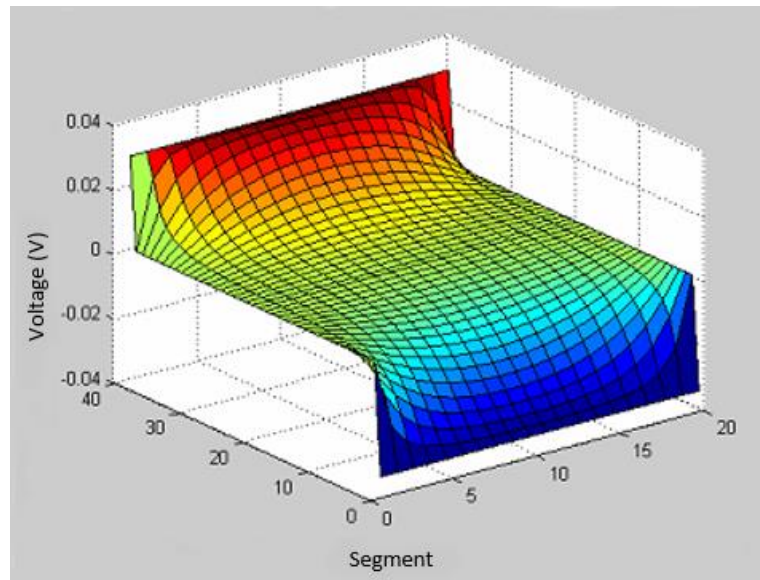


Figure 3-5 Potential Difference between N- type and P-type TE Couples.

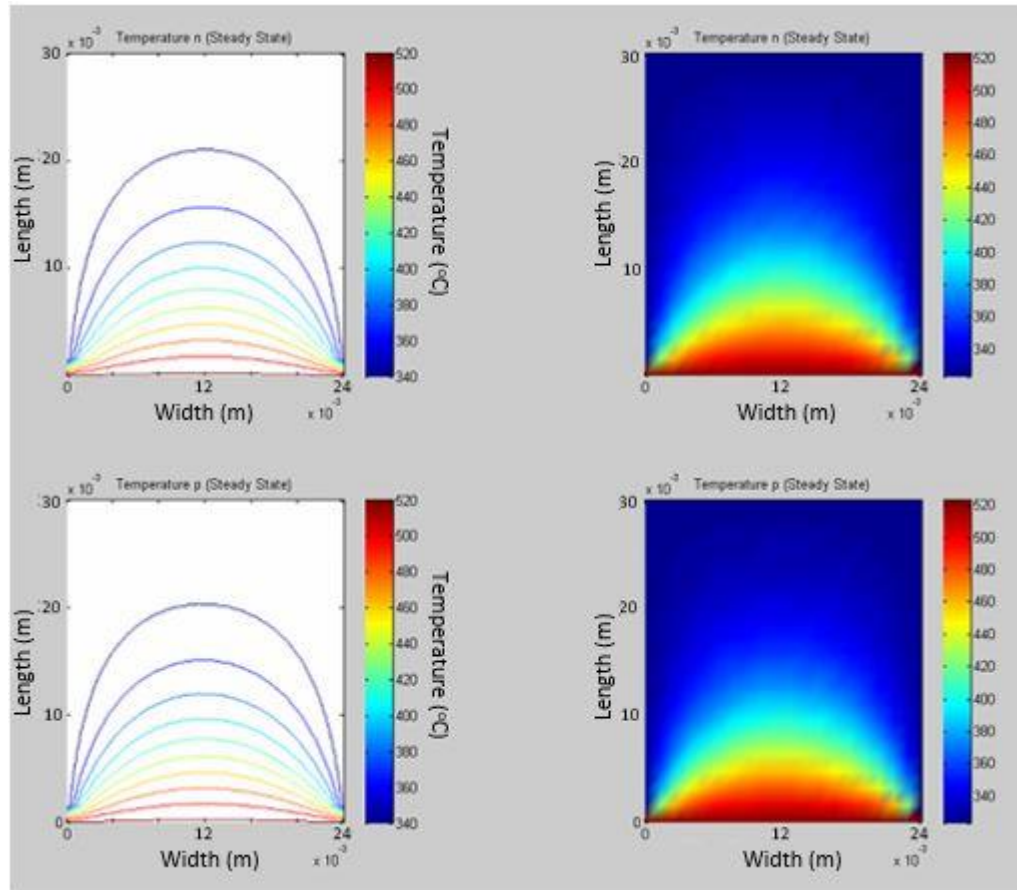


Figure 3-6 Steady State Temperature Distribution of TE Couple.

To solve the heat transfer equation, the finite difference equations (FDE) method is applied into the program. In FDE, a temporary heat derivation is determined and then used as the variance between current time and previous time values. In addition, the input values are set according to the user input and are adjustable for different conditions. The configuration screen is displayed in Fig 3.7.

```

set n value      :20
set thermoelectric leg length value (mm) : 1.5
set thermoelectric leg width value (mm) : 1.2
set thermoelectric leg depth value (mm) : 1.2
set heat convection coefficient value (W/m.k) (5 to 20) :15
set hotside temperature of TE leg (K) :523
set coldside temperature of TE leg (K) :323
set current though TE leg (Amp) :0.5

```

Figure 3-7 Configuration of TE specification inputs.

3.2.3 Two-Dimensional Transient Heat Transfer Simulation

The two-dimensional heat transfer simulation demonstrates that the central nodes of the TE couple have a higher temperature than the corner nodes because of the contact of the ambient temperature and the outer surface of the TE couple. This variance explains the measured different temperature values of the different positions in the laboratory experiment and this information is obtained by applying the ambient temperature effect into the formula.

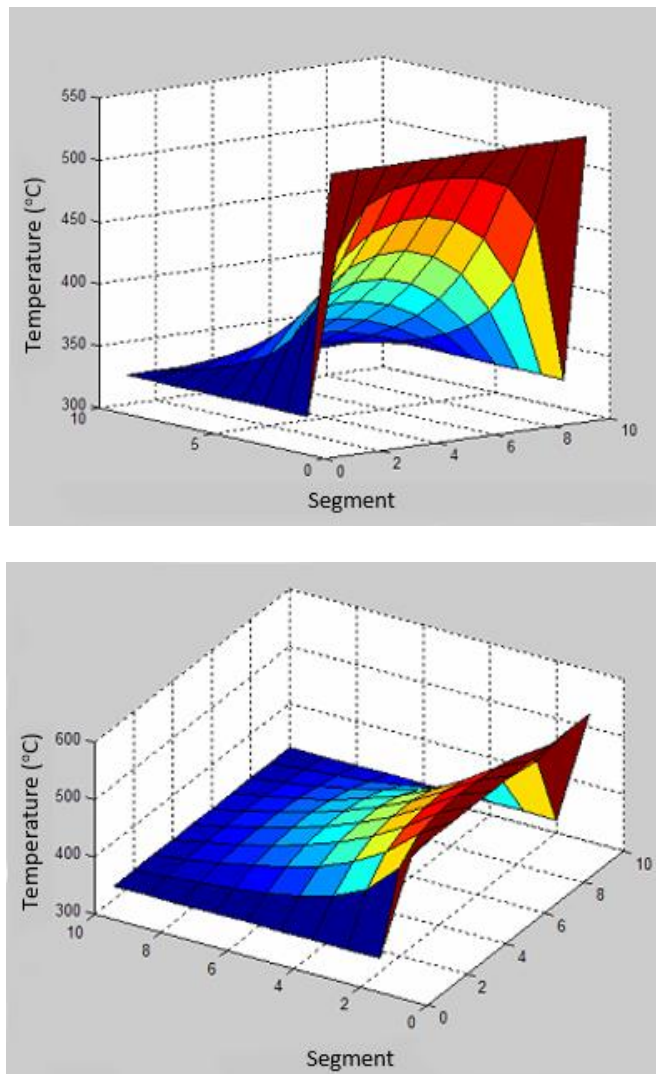


Figure 3-8 Transient heat distribution of 2-D TE couple.

The transient heat transfer simulation provides a temperature distribution in time and two directions and it illustrates how the heat is shifted from the hot side to cold side. The transient heat transfer formula which is obtained from Eq. (3.40) is represented in Eq. (3.41).

$$\begin{aligned}
& A \frac{d}{dx} \left[(\kappa_n + \kappa_p) \frac{dT}{dx} \right] + \frac{l^2}{A} (\rho_n + \rho_p) + I(\tau_n - \tau_p) \frac{dT}{dx} - 2hp \left(T - T_c - \frac{T_h - T_c}{L} x \right) + \\
& A \frac{d}{dy} \left[(\kappa_n + \kappa_p) \frac{dT}{dy} \right] + \frac{l^2}{A} (\rho_n + \rho_p) + I(\tau_n - \tau_p) \frac{dT}{dy} - 2hp \left(T - T_c - \frac{T_h - T_c}{L} y \right) = \\
& A_p C_p \rho_p \frac{\delta T_p}{\delta t} + A_n C_n \rho_n \frac{\delta T_n}{\delta t}
\end{aligned} \tag{3-41}$$

3.2.4 Voltage Output Comparison of Simulation and Actual Data

The voltage output of the simulation, shown in Fig 3.5 is 0.07 V for a single thermocouple with a hot side temperature of 250°C and a cold side temperature of 50°C. In addition, the parameters of Th=250°C and Tc=30°C, shown in Table 3-1 [53], and the matched load voltage graphic, shown in Fig 3.9 [53], are used to compare results between the simulation and the datasheet values.

Table 3-1 Output values of TE parameters when Th=250°C and Tc=30°C.

Matched load resistance	3.65Ω ± 15%
Open circuit voltage	10.11V
Matched load output	1.38A
Matched load output voltage	5.05V

Heat flow through module	139.8W
Maximum compress (non-destructive)	1.2MPa
Maximum operation temperature	Hot side is 250°C Cold side is 175°C

The simulation output voltage is calculated by:

$$\begin{aligned}
 V_{load} &= \frac{N}{2} \cdot (V_n + V_p) \\
 &= \frac{127}{2} \cdot 0.07 = 4.445V
 \end{aligned} \tag{3-42}$$

where N is number of thermocouples and ($V_n + V_p$) is obtained from Fig 3.5. The load voltage of the simulation is 4.445 at a 200°C temperature difference and the load voltage of the datasheet is 5.05V at a 220°C temperature difference, a decrement of dT would cause a decrease in output load voltage, dV, which is shown in Fig 3.9. A comparison of the two results, shows that an accuracy of more than 90% is obtained in the simulation result.

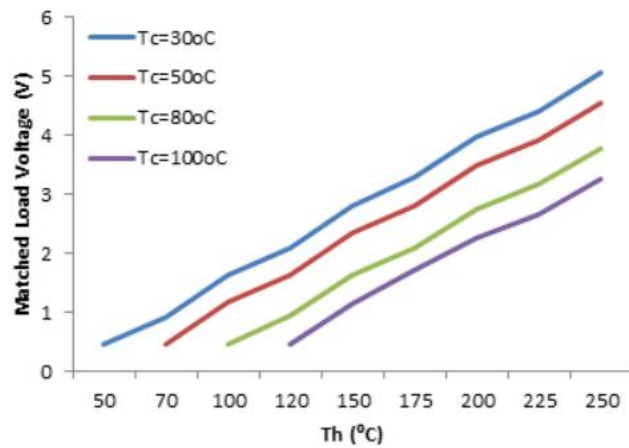


Figure 3-9 Matched load voltage of GM250-127-14-16. [53]

Chapter 4 Methodology of DC-DC Power Converter

In this chapter, the methodologies applied in DC-DC conversion are described. In the first part, the most common power converters are introduced: the linear regulators. In the second part, switching converters are presented and examined. Lastly, in the third part, the controllers of the switching converters are analysed and their various regulation topologies are described.

As shown in Figure 4.1, each electronic power converter comprises of a power processor, a controller, and a voltage reference [53]. The input voltage which is provided by a power supply, is converted by the power processor and transmitted to the load. The power stage, which is also titled as the power processor, can be a voltage, frequency or current converter and comprises of the power electronic parts, as explained in chapter 6. By comparing the reference voltage and output voltage, the error voltage is generated by the feedback controller to maximise

efficiency at the output. Switching and linear regulators consist of this main regulation method. The control mechanism in these type of conversion topologies is based on an analogue signal and system which are mostly operated by an op-amp comparison and error amplifier. In advanced system, the analogue parts are replaced with microcontrollers, as in our project, and the control mechanism becomes more complicated and reliable. However, advanced controllers are not suitable for low level applications due to their cost efficiency.

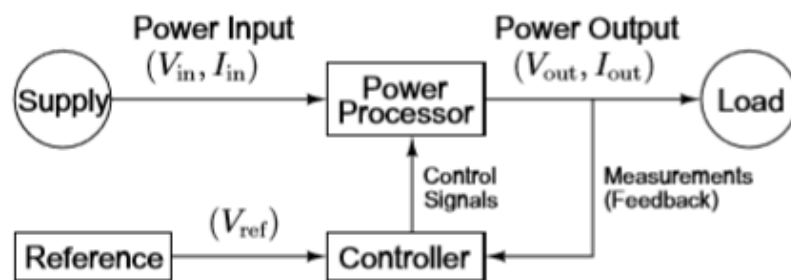


Figure 4-1 Power conversion system block diagram. [53]

4.1 Linear Voltage Regulators

A constant DC voltage is transmitted to a load by a linear voltage regulator. Disregarding the variance of the input current and voltage, the linear voltage regulator adjusts the voltage level to required level. Nevertheless, the success of their operation relies on reasonable variance at the input and load voltage and load current.

Price-wise, the linear regulator is inexpensive and it is simple to use and also proposes a low ripple at load voltage. Thus, it can be chosen for noise sensitive

systems such as frequency related designs in telecommunication systems. To obtain a better load and line regulation, line regulators are a preferred method because they respond to line variances and transient loads rapidly. Line regulators do not propagate electromagnetic interferences (EMI) due to their system which non-switching regulator. The disadvantage of a linear regulator is its low performance, which implicates high power dissipation and it causes increase in the size of the design because of the large heatsink requirement.

4.1.1 Operating Principle

In Fig. 4.2, a linear voltage regulator consisting of a reference voltage, power transistor and an error booster including a resistive feedback, which in turn consists of feedback resistances 1 and 2, is shown. To calibrate the steadiness in the loop, a capacitor (C_{out}) is placed into the system.

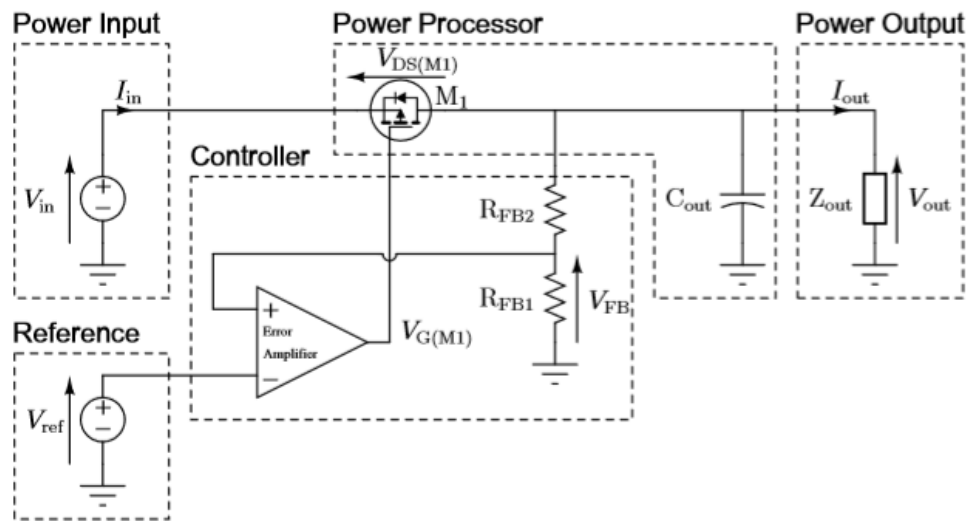


Figure 4-2 Schematic of a linear voltage regulator. [81]

The power transistor (PMOS) behaves like a tuneable resistance. The error booster alters the power transistor gate value, thereby the required output voltage

magnitude is supplied by a voltage drop through the PMOS. The gain of the resistive feedback section assigns a regulated voltage magnitude. The purpose of the error booster is to match the demanded output voltage with the reference voltage, thus the output voltage is given by:

$$V_{OUT} = V_{REF} \frac{R_{FB1} + R_{FB2}}{R_{FB1}} \quad (4-1)$$

4.2 Switching Voltage Converters

Switching regulator systems consist of passive components such as magnetic and capacitive elements to store energy, oscillators to produce clock signals and active components as a switch. Theoretically 100% efficiency can be reached by switching converters if the switching components parasitic effect is considered as negligible. In practice, the switching converter power conversion efficiency is only decreased by a parasitic effect, dissimilar to a linear regulator, in which the power transistor is applied as a variable resistor.

There are two basic kinds of switching regulators. The most basic one is the inductorless converter, also known as a charge pump, consists of capacitive and switching parts. In integrated circuits this kind of converters are mainly applied for dividing or multiplying the input voltage with better performance than a linear regulator. Inductorless converters are mainly low power converter which operate the active switching process with MOSFETs.

A DC-DC converter which includes both magnetic passive components and capacitive elements integrated with active switching parts has a more effective and flexible switching regulation. The magnetic components are mainly separate power coils (inductors) or power transducers (transformers) and capacitive components which can be combined or placed separately. Various active components are placed to obtain such converters, depending upon the implementation requirements. These components are diodes, thyristors and transducers.

4.2.1 Inductorless Converters

DC-DC converters consist of inductors and capacitances whereas charge pumps only use capacitances. Charge pumps, which comprise of power switching components and capacitances in the power processor are low power converters. An inductorless converter operates through several switched lines which are repeatedly switched on and off. This methodology is not suitable for high power converters due to the lack of inductors. This kind of converter can be placed into a single silicon chip and its output power can operate in the milliwatt range. The area of the silicon used by inductorless converter and its on-chip MOS capacitances, that compose the switched capacitance line, are important in its operation. Nevertheless, metal-metal capacitances (MMC) are a better selection for Mixed-signal design in deep submicron digital CMOS technology because the MMC supplies more breakdown voltages and less ESR (equivalent series resistor) so it provides better performance.

One of the main benefits of the charge pumps is that they do not have EMI and magnetic fields which is due to the transducer and inductor. The disadvantage of these converters is that they cannot supply better performance as converters if the required voltage conversion factor is not an integer.

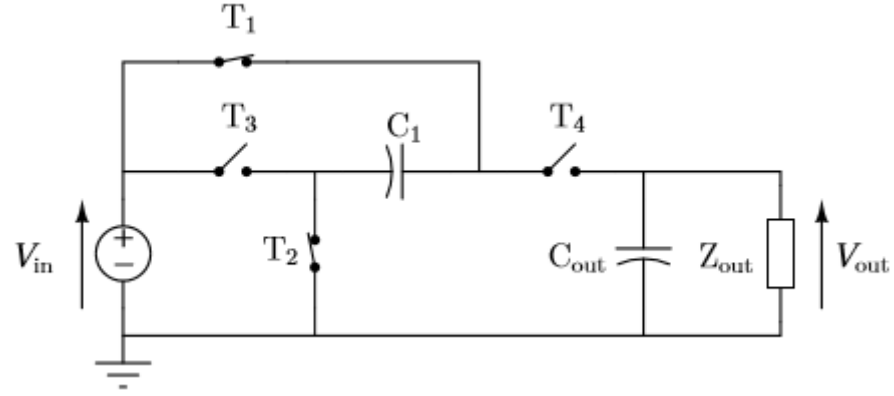


Figure 4-3 Voltage doubler schematic. [82]

The schematic represented in Figure 4.3 indicates a simple voltage doubler with switched capacitors [39]. In the first stage, the input voltage charges capacitor C_1 when switch 1 and 2 are on. In the second stage, stored energy in C_1 during the first stage and power supply integrate and charges the output capacitor when switch 3 and 4 are on. For this reason, the input voltage duplicates at the output of the converter so ratio of the maximum voltage conversion (M) is described as:

$$M = \frac{V_{OUT}}{V_{IN}} = 2 \quad (4-2)$$

4.2.2 Basic DC-DC Converter Topologies

In the upcoming methodologies, operating in a steady-state with a constant input and output voltage level are made as assumption for converters throughout. In

addition, devices placed in the system are assumed to be optimum and have no interference, such as a zero or infinite resistive value for some components during the switching operation.

A sophisticated DC-DC converter architect builds on three basic methodologies which are the boost converter, the buck boost converter and the buck converter, some of the converters provide a polarity inverting at output. While the boost converter methodology supplies higher output than input voltage, a buck converter methodology supplies less output than input voltage. Integrated buck-boost converter methodology can provide both high and low level voltage at the output.

Inductor, capacitors and transducers which store energy, are the most significant components for power supplies which use a switching operation. Inductors which consist of two different types of material, powder core and ferrite core, with a distributed air-gap to minimize core losses at high frequencies, are included in switching regulators. Due to size and weight disadvantages, transducers are mainly applied into isolated systems, but in this project non-isolated methodologies which use inductor and capacitance are examined in spite of these disadvantages.

Energy is stored by a capacitor in an electrical field, which evolves by supplying voltage to the capacitor ports. The energy storage function as an electric field and generated voltage varies due to this storage is named as capacitance. As shown in Eq. (4-3), the current circulates along the capacitor is related to the voltage variance ratio of the capacitor ports.

$$I_{C1}(t) = C_1 \frac{d}{dt} V_{C1}(t) \quad (4-3)$$

Energy is stored by an inductor in a magnetic field, which evolves by current flowing across the inductor. The energy storage function as a magnetic field and generated current varies due to this storage is titled as inductance. As shown in Eq. (4-4), the voltage variance of the inductor ports is related to ratio of the current flow along the inductor.

$$V_{L1}(t) = L_1 \frac{d}{dt} I_{L1}(t) \quad (4-4)$$

In portable implementations, a battery supplies voltage variance at the power input, however any DC power supply can be placed as well. As shown in Fig 4.4 a switching system composes of reactive components such as capacitance and inductors and switches, such as power transistors and power diodes, and the output of the converter consists of a load which is an impedance. The PWM controller unit consist of a feedback loop, a buffer, which is power transistor gate driven system and a PWM section. The loop compensator, feedback and reference voltage create the feedback loop and a pulse width modulator comparator, oscillator and error amplifier make up the PWM section.

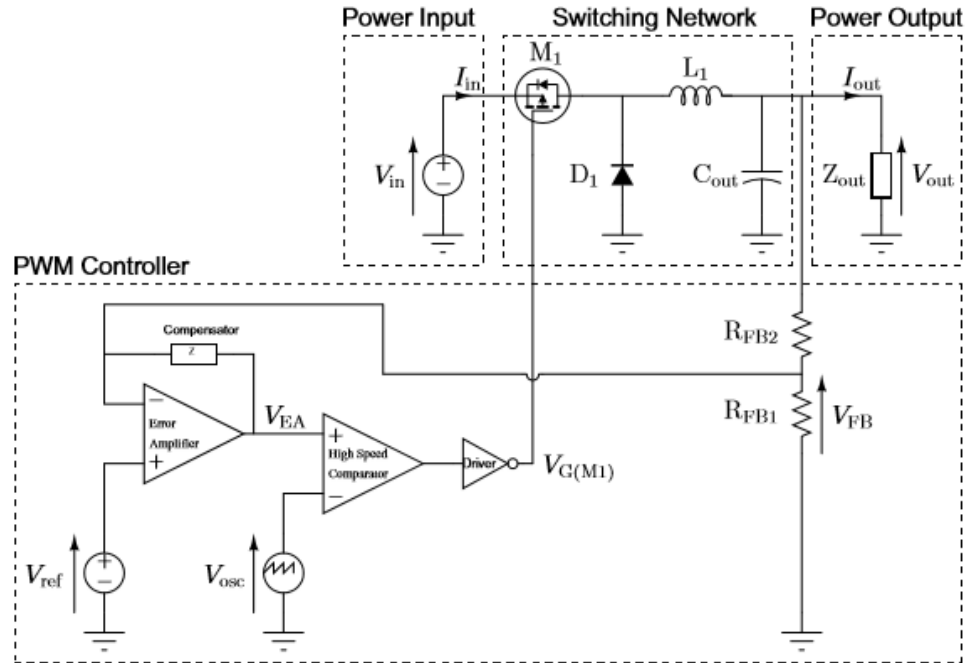


Figure 4-4 Buck converter with PWM controller. [83]

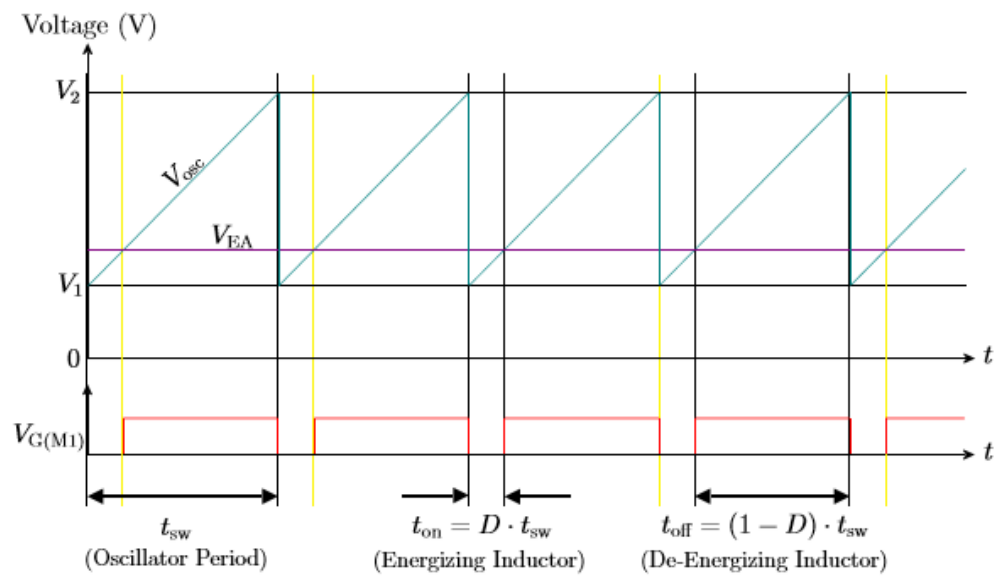


Figure 4-5 Transistor gate voltage. [83]

Figure 4.5 displays sawtooth oscillator voltage levels which are V_1 and V_2 and produce an analogue signal wave. A comparison between the output voltage of

the error amplifier (V_{ea}) and the sawtooth wave composes a power transistor gate driven signal (V_g). The sawtooth wave period is indicated by t_{sw} , the inductor charging period when the transistor is in the on position is indicated with t_{on} and the inductor discharging period when transistor is in the off position is indicated by t_{off} . In addition, the proportion of t_{on} to t_{sw} represents the duty cycle of the switching system.

4.2.2.1 Buck Converter

In Fig 4.6, the basic step down switching methodology of the buck converter is presented. The power diode provides a continuous current in the inductor, the filter capacitance, which decreases the ripple of the output voltage and the power transistor, which switches the charging operation of the inductor, all compose the buck converter. In addition, the DC voltage source supplies power into converter and a load causes an impedance to the converter output.

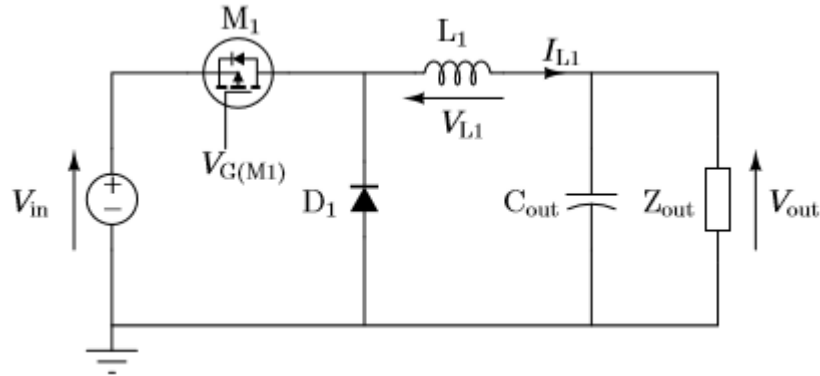


Figure 4-6 Schematic of Buck converter. [84]

The PWM controller system illustrated in Fig 4.4 can regulate the voltage output of the converter. This system accomplishes its process by producing a pulse width modulation wave according to the voltage feedback from the output. The

current flow of the inductor boosts when the charging power transistor (MOSFET) is switched on and the flyback diode D1 is reverse biased. The current through the inductor reduces and the flyback diode turns into forward biased when the transistor switches on. A continuous conduction mode (CCM) operating system can be achieved by preventing a zero cross current on the inductor. Discontinuous conduction mode (DCM) can occur when the inductor current crosses zero because the flyback diode prevents a negative current flow and it causes a discontinuity. In addition, these conduction modes are related to the impedance of the load. The conduction modes are shown in Fig. 4.7.

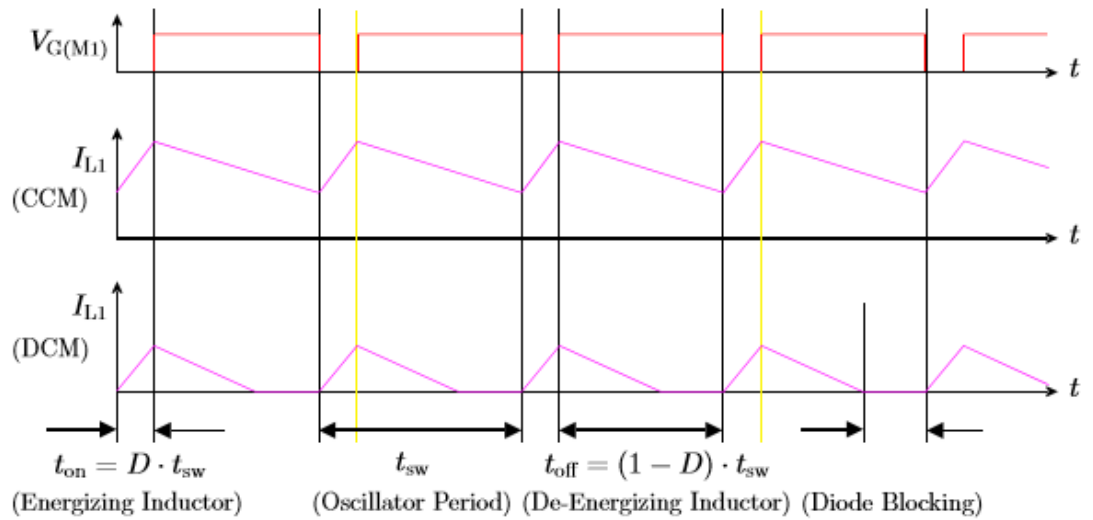


Figure 4-7 Inductor currents at CCM and DCM in steady state condition. [85]

A built-in MOSFET diode is not applied to the buck converter. On the other hand, a built-in diode is mandatory for H-bridge converter methodologies. The converter transfer function is the ratio of the output of a system to the input of a system and is illustrated under a steady-state operation condition and CCM assumptions.

$$\begin{cases} t_{SW} = t_{ON} + t_{OFF} \\ D = \frac{t_{ON}}{t_{SW}} \end{cases} \quad (4-5)$$

To define the relationship between input and output voltages, they must be examined in two stages of the switching operation.

- Stage 1: Switch is on and diode is reverse biased ($0 < t < t_{on}$):

$$V_{L1} = V_{IN} - V_{OUT} \quad (4-6)$$

- Stage 2: Switch is off and diode is forward biased ($t_{on} < t < t_{sw}$):

$$V_{L1} = -V_{OUT} \quad (4-7)$$

While voltage variance across inductor is calculated by $V_{L1}(t) = L_1 \frac{d}{dt} I_{L1}(t)$ as mentioned in Eq. (4-4), the inductor current is calculated by modifying this formula:

$$I_{L1}(t_{SW}) - I_{L1}(0) = \frac{1}{L_1} \int_0^{t_{SW}} V_{L1}(t) dt \quad (4-8)$$

The first and final amount of the inductor current are assumed to be equal in the steady-state condition, thus integration of the inductor voltage is zero:

$$0 = \int_0^{t_{SW}} V_{L1}(t) dt = \int_0^{t_{ON}} V_{L1}(t) dt + \int_0^{t_{OFF}} V_{L1}(t) dt \quad (4-9)$$

In the theory, all the components considered to be ideal therefore the output voltage ripple is equal to zero and the inductor voltage is assumed to be constant between the two stages. Integration of the above-mentioned equations and assumptions gives:

$$\int_0^{t_{ON}} V_{L1}(t)dt + \int_0^{t_{OFF}} V_{L1}(t)dt = 0 \quad (4-10)$$

Integration of the constant input and output voltage assumptions and the above-mentioned equation gives:

$$(V_{IN} - V_{OUT})(t_{ON} - 0) - V_{OUT}(t_{SW} - t_{ON}) = 0 \quad (4-11)$$

$$V_{IN}t_{ON} - V_{OUT}t_{SW} = 0 \quad (4-12)$$

The duty cycle of the buck converter is illustrated with use of the above-mentioned equation by:

$$M_{BUCK} = \frac{V_{OUT}}{V_{IN}} = \frac{t_{ON}}{t_{SW}} = D \quad (4-13)$$

4.2.2.2 Boost Converter

The methodology of the step up converter, illustrated in Fig. 4.8, is applied into the system when a higher voltage output is required according to a voltage input. The inductor current value rises when the charging MOSFET is switched on and the diode is reverse biased. During the switch to off mode, the current across the inductor is transmitted to the load and the diode turns into forward biased.

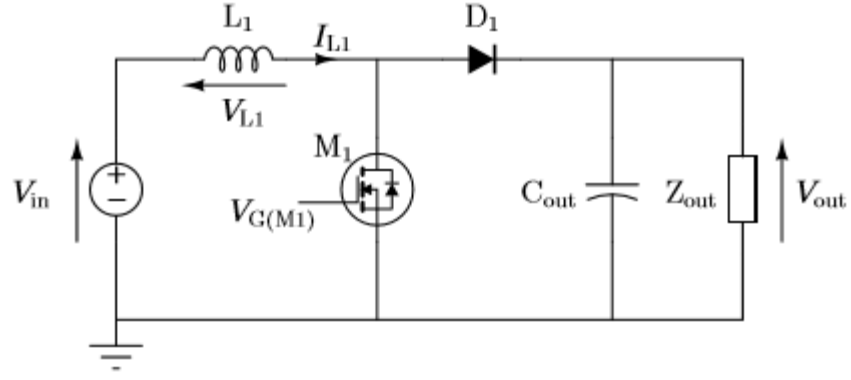


Figure 4-8 Schematic of Boost converter. [86]

By putting the inductor on the input side the ripple at the input current is decreased, but it increases ripples at the output current. Within the assumption of the steady-state condition and continuous conduction mode and consideration of the similar approach to the buck converter, the conversion ratio and duty cycle of the system is illustrated:

$$M_{BOOST} = \frac{V_{OUT}}{V_{IN}} = \frac{t_{SW}}{t_{SW} - t_{ON}} = \frac{1}{1-D} \quad (4-14)$$

4.2.2.3 Inverting Buck-Boost Converter

In the buck-boost converter, both lower and higher voltage outputs are provided corresponding to the input voltage. The diagram of the buck-boost converter is shown in Fig. 4.9. In the first state, the charging MOSFET is switched on, the diode is reverse biased and the inductor current steps up. In the second state, the charging MOSFET is switched off, the diode is forward biased and the current is drained by the inductor across the diode which causes a negative voltage at the output. Through similar assumptions and operating conditions, the conversion ratio of the buck boost converter can be illustrated:

$$M_{BUCK-BOOST} = \frac{V_{OUT}}{V_{IN}} = \frac{-t_{ON}}{t_{SW}-t_{ON}} = \frac{-D}{1-D} \quad (4-15)$$

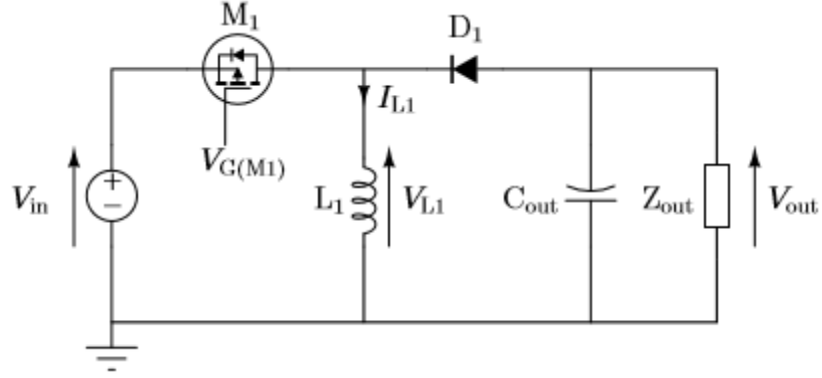


Figure 4-9 Schematic of Inverting Buck-Boost converter. [87]

4.2.3 Advanced DC-DC Converter Topologies

Commonly used portable systems are energised by lithium-ion batteries supplying voltage levels between 3V and 4.2V for the operation of 3.3V systems. For this reason, both boost and buck ability converters are mainly considered in advanced DC-DC converter applications which include multi storage components and switching parts.

4.2.3.1 Noninverting Buck-Boost Converter

A noninverting buck-boost converter is obtained due to an additional switching part added to the inverting buck-boost converter and it integrates both step up and step down converters together. In state 1, the charging transistors are switched on, the current across the inductor boosts and both diodes are reverse biased. In state 2, both charging transistors are switched off and the diodes are forward biased while the output power is produced by the inductor current. Both switch gates are activated with same signal and they are controlled at the same

time in the main noninverting applications, however the other gate driven systems are applicable. As a result of both PMOS and NMOS transistor usage, the control system is more complicated than the methodologies that are mentioned above.

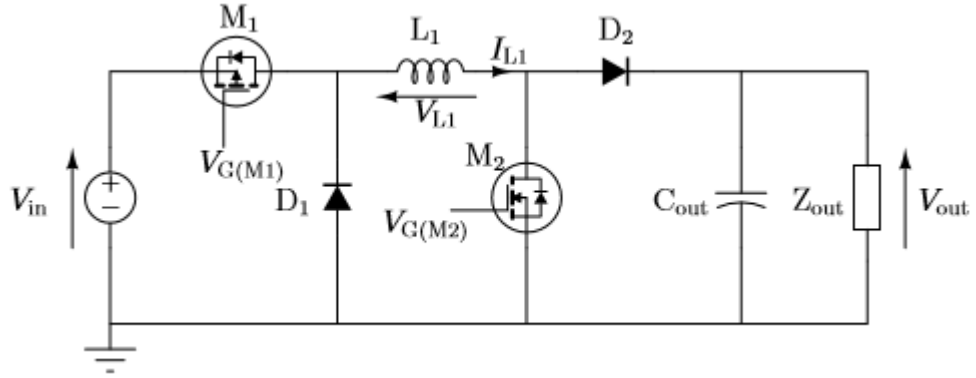


Figure 4-10 Schematic of noninverting Buck-Boost converter. [88]

The conversion ratio of noninverting Buck-Boost converter can be illustrated by applying a similar methodology as with the buck converter in section 4.2.2 as follows:

$$M_{BUCK-BOOST} = \frac{V_{OUT}}{V_{IN}} = \frac{t_{ON}}{t_{SW}-t_{ON}} = \frac{D}{1-D} \quad (4-16)$$

4.2.3.2 Ćuk Converter

In addition to step up and step down converting ability, the Ćuk converter can also invert the polarity of the input. In stage 1, the transistor is switched on, current across the inductors is boosted and the diode becomes reverse biased, the current of the second inductor is transmitted to the load. In stage 2, the transistor is switched off, the capacitor is energised and the diode is forward biased

- Stage 1: transistor is switched on; diode becomes reverse biased ($0 < t < t_{on}$):

$$\begin{cases} V_{L1} = V_{IN} \\ V_{L2} = V_{OUT} + V_{C1} \end{cases} \quad (4-17)$$

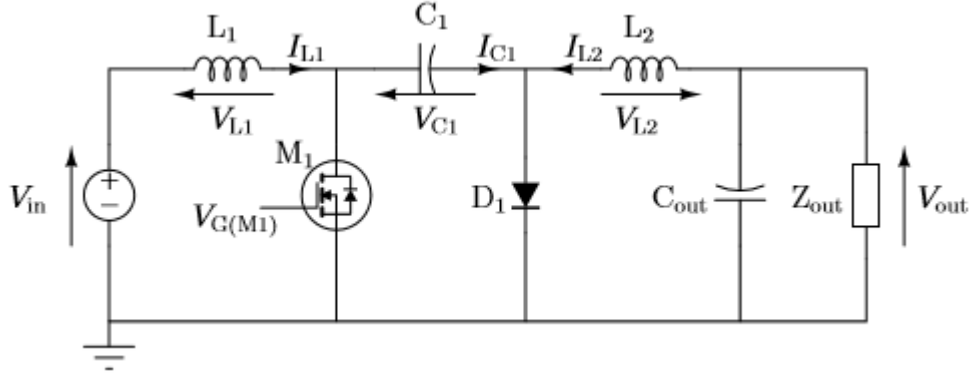


Figure 4-11 Schematic of Ćuk converter. [89]

- Stage 2: Transistor is switched off and diode becomes forward biased
($t_{on} < t < t_{sw}$):

$$\begin{cases} V_{L1} = V_{IN} - V_{C1} \\ V_{L2} = V_{OUT} \end{cases} \quad (4-18)$$

To obtain a negligible voltage ripple through the capacitor, the capacitance value must be chosen to be high enough during the steady-state operation. Therefore, the voltage values of the inductors are also stable during switch on and off positions with a discontinuity step at the switching moment. The current of the inductor varies across the second inductor throughout the steady-state condition as is illustrated in Fig 4.11.

$$\int_0^{t_{on}} V_{L2}(t) dt + \int_{t_{on}}^{t_{sw}} V_{L2}(t) dt = 0 \quad (4-19)$$

Integration of equation 4-17 and 4-18 and adopting into equation 4.19 the following equation is derived:

$$\int_0^{t_{ON}} V_{OUT} + V_{C1}(t) dt + \int_{t_{ON}}^{t_{SW}} V_{OUT} dt = 0 \quad (4-20)$$

Integration of equation 4-20:

$$(V_{OUT} + V_{C1})(t_{ON} - 0) + V_{OUT}(t_{SW} - t_{ON}) = 0 \quad (4-21)$$

$$V_{C1} = -V_{OUT} \frac{t_{SW}}{t_{ON}} \quad (4-22)$$

The current variance across the first inductor in the steady-state condition is illustrated:

$$\int_0^{t_{ON}} V_{L1} dt + \int_{t_{ON}}^{t_{SW}} V_{L1} dt = 0 \quad (4-23)$$

Integration of equation 4-17 and 4-18 into equation 4-19 the following equation is obtained:

$$\int_0^{t_{ON}} V_{IN} dt + \int_{t_{ON}}^{t_{SW}} (V_{IN} - V_{C1}) dt = 0 \quad (4-24)$$

Integration of equation 4-24:

$$V_{IN}(t_{ON} - 0) + (V_{IN} - V_{C1})(t_{SW} - t_{ON}) = 0 \quad (4-25)$$

$$V_{IN}(t_{ON} - 0) + \left(V_{IN} + V_{OUT} \frac{t_{SW}}{t_{ON}} \right) (t_{SW} - t_{ON}) = 0 \quad (4-26)$$

$$V_{IN}t_{SW} + V_{OUT} \frac{t_{SW}}{t_{ON}} (t_{SW} - t_{ON}) = 0 \quad (4-27)$$

As a result of equation 4-27 the Ćuk converter's conversion ratio is:

$$M_{\acute{C}uk} = \frac{V_{OUT}}{V_{IN}} = \frac{-t_{ON}}{t_{SW} - t_{ON}} = \frac{-D}{1-D} \quad (4-28)$$

The first coil of a Ćuk converter is linked to the input and the second coil is linked to the output, therefore the ripples of the input and output currents

decrease by these links. A bidirectional converter can be achieved by changing the diode with a power transistor. The requirement of two coils and extra capacitance is a disadvantage of the Ćuk converter.

4.2.3.3 SEPIC Converter

A SEPIC converter is established by inserting additional components, which are an inductor and a capacitor into the step up converter methodology. The capacitance which is placed between the diode and the first inductor prevents a DC current flow between these components. In addition, an inductor is placed between the diode and the ground requirement of the DC voltage for the anode port of diode. A SEPIC converter can supply both higher and lower voltage outputs than the input.

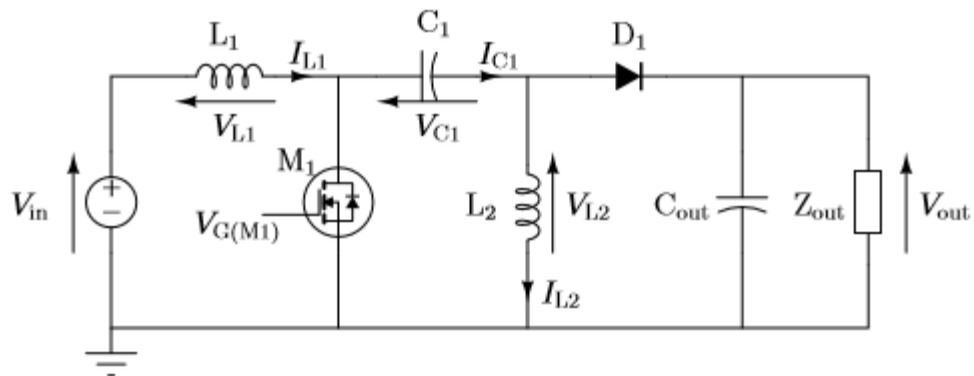


Figure 4-12 Schematic of SEPIC converter. [90]

In t state 1, the charging MOSFET is switched on, the power supply current flows through the first inductor and the capacitor discharges through the second inductor so the voltage builds up in the inductor and also the diode becomes reverse biased. In state 2, the charging MOSFET is switched off, the diode becomes forward biased and the inductors provide power to the output and also

the capacitance is energized by the first inductor. By applying a similar topology of the Ćuk converter, the SEPIC converter conversion is illustrated by:

$$M_{SEPIC} = \frac{V_{OUT}}{V_{IN}} = \frac{t_{ON}}{t_{SW}-t_{ON}} = \frac{D}{1-D} \quad (4-29)$$

A low input current ripple is achieved due to the connection of the power supply and the inductor in the SEPIC converter methodology, however a high ripple at the current output occurs due to a lack of a connection between the converter output and the inductor.

4.2.3.4 H-Bridge Converter

A Full-Bridge, also called H-Bridge converter methodology can be used as step up, step down and a buck-boost converter due to its driving configuration capability which is shown in Fig. 4.13. A H-Bridge converter, which has a symmetrical design, is established on the buck-boost methodology, which is illustrated in Fig. 4.14. One of the major advantages of this converter is that it has both charging and discharging modes due its symmetrical design.

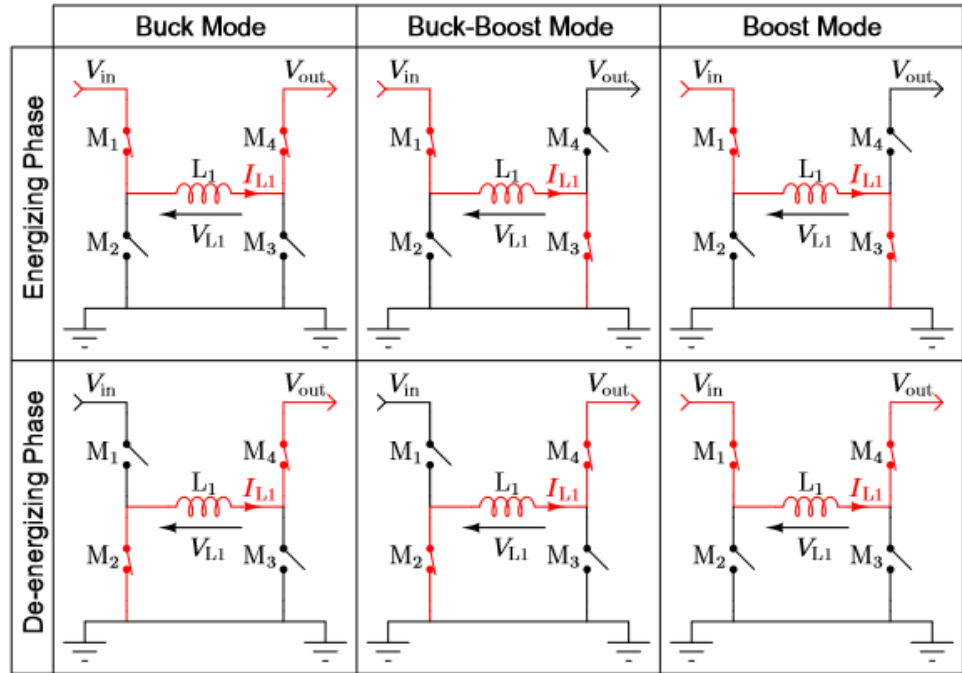


Figure 4-13 H-Bridge converter switching operations. [91]

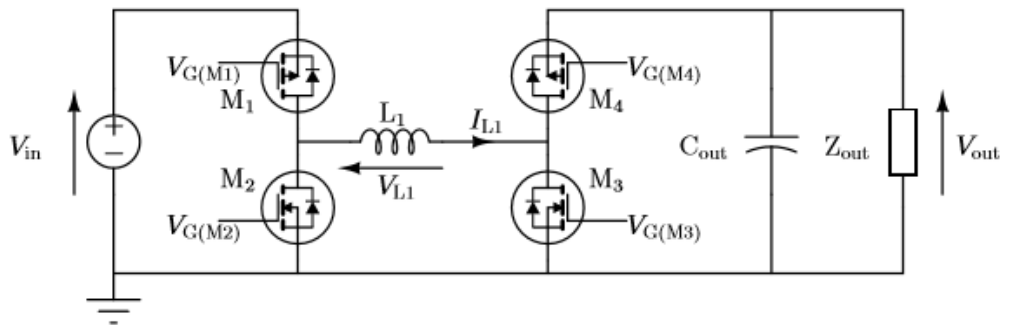


Figure 4-14 Schematic of H-Bridge Converter. [91]

As it relies on only one inductor, the Full-Bridge converter could be chosen for integrated DC-DC converters. Some of the H-Bridge advantages are high performance, less amount of passive components and both high and low conversion ability and flexibility. Due to these advantages this project uses the full bridge methodology. Nevertheless, the Full-Bridge methodology has some

disadvantages as well. A minimum voltage which depends on the MOSFET specifics is required at the transistor's source and ground ports if p-type MOSFETs are placed as the high side switches. A switch regulator must supply enough gate driven voltage to activate the transistor if n-type MOSFETs are placed as the high side switches. Another disadvantage is the necessity of a shoot through protection system which is computed and applied into system in this project. Further details are shown in chapter 6.

Chapter 5 Thermoelectric Power Generation Simulation

The purpose of the TE power generation simulation is to improve the accuracy of the estimation values before building an actual test rig. One can choose the necessary components based on the simulated values, determine the maximum conditions and compare the simulated with the actual values to realise possible loss parameters. Especially in electronic designs if there is a fault in the system, a simulation examination is the one of the best ways to address the fault and find a solution. In this simulation, a thermoelectric power generator simulation is established on full scale TEG test rig design, which determines the number of thermoelectric module as well as other parameters. The Hi-Z 20 thermoelectric module, which has similar parameter values to the actual test rig thermoelectric modules is used to achieve the simulation results.

5.1 Simulation Steps

The TE module simulation is initiated by applying the characteristics of the TE into the system, after which the program starts to realise the parameters of a single TE couple within the 20 nodes of each pellet to the improve accuracy. To obtain a single TE module's parameters, which has 142 legs, 2840 iterations of the TE characteristics are analysed and computed for each temperature gradient. Considering the full scale TEG test rig design, a half scale model of the TEG is designed in the simulation. It has 40 TE modules and each module is faced with different hot side temperature values, which are derived from the test rig 4 computational fluid dynamics (CFD) design. In addition to the different temperature values of each block, variated exhaust gas temperatures, which are

derived from the ADVISOR software that provides automotive thermal output values according to a new European driving cycle (NEDC), are also applied into the system to provide a real time simulation. Consequently, to obtain the TEG output parameters for a single temperature gradient, the program runs 113600 TE characteristic iterations and for real time response which has 1183 temperature values the program runs more than 133 million iterations.

5.1.1 TE module power generation calculation

In this simulation, a single TE module is initially simulated at 350°C hot side temperature and 50°C cold side temperature. In the beginning of the coding Hi-Z 20 parameters are uploaded into the MATLAB simulation. These parameters are Seebeck (α), resistivity (ρ) and thermal conductivity (k) coefficients and the physical structures of the TE are given in Table 5-1 and Table 5-2.

Table 5-1 Manufacturer Seebeck, thermal conductivity, electrical resistivity coefficient values.

Coefficient values of Hi-Z 20		Bi₂Te₃ N	Bi₂Te₃ P
α_1	V/K	7.42E-05	-0.00026
α_2	V/K	-1.5E-06	2.32E-06
α_3	V/K	2.94E-09	-3.18E-09

α_4	V/K	-2.50E-12	9.17E-13
α_5	V/K	1.36E-15	-4.88E-16
ρ_1	Ohm.cm	-0.00196	-0.00285
ρ_2	Ohm.cm	1.79E-05	1.97E-05
ρ_3	Ohm.cm	-3.82E-08	-3.32E-08
ρ_4	Ohm.cm	4.92E-11	3.47E-11
ρ_5	Ohm.cm	-2.98E-14	-1.90E-14
k_1	W/m-K	1.425785	6.924575
k_2	W/m-K	0.006515	-0.05119
k_3	W/m-K	-5.2E-05	0.0002
k_4	W/m-K	1.12E-07	-3.89E-07
k_5	W/m-K	-7.60E-11	3.04E-10

Table 5-2 TE module structure parameters.

Architecture Parameters of Hi Z-20	
leg width 1	0.495 cm
leg width 2	0.495 cm
leg length	0.267 cm
connector width	0.5 cm
connector thickness	0.15 cm
connector resistivity	2.63E-06 Ω .cm
number of legs on side 1	12
number of legs on side 2	12
thickness of eggcrate wall	0.06 cm

height of eggcrate wall	0.58 cm
thermal conductivity of eggcrate	0.1 W/m-K

The TE generator simulation is executed in one direction by dividing the pellet lengths into 20 segments to increase the calculation accuracy and each segment is represented by an `i` value which is 1 to 20. The Seebeck coefficient of the TE is calculated by using the quadratic fourth order equation in Eq. (5-1) and Eq. (5-2) for p and n pellets.

$$\alpha_{n_i} = \alpha_{coef1_n} + \alpha_{coef2_n}T_{avg_i} + \alpha_{coef3_n}T_{avg_i}^2 + \alpha_{coef4_n}T_{avg_i}^3 + \alpha_{coef5_n}T_{avg_i}^4 \quad (5-1)$$

$$\alpha_{p_i} = \alpha_{coef1_p} + \alpha_{coef2_p}T_{avg_i} + \alpha_{coef3_p}T_{avg_i}^2 + \alpha_{coef4_p}T_{avg_i}^3 + \alpha_{coef5_p}T_{avg_i}^4 \quad (5-2)$$

where T_{avg_i} is the average of the previous and current segments temperature values and α_{coef} values are obtained from Table 5-1 and Table 5-2 which is given by the manufacturer.

Due to the implementation of Eq. (5-1) and Eq. (5-2) the change of Seebeck parameter during transient mode is illustrated in Fig. 5.1.

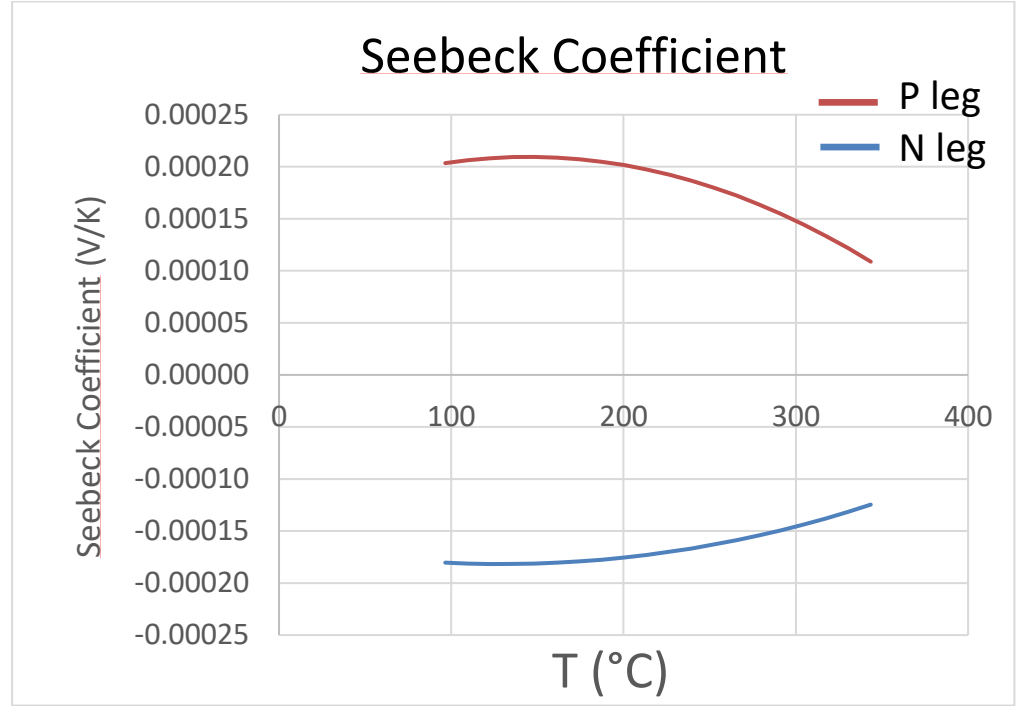


Figure 5-1 Seebeck Coefficient values of p and n pellets.

The electrical potential calculation based on the Seebeck coefficient is applied to the TE in segments for each leg, which is given by:

$$V_{n,i} = \alpha_{n,i} \cdot \Delta T_{seg} \quad (5-3)$$

$$V_{p,i} = \alpha_{p,i} \cdot \Delta T_{seg} \quad (5-4)$$

where, ΔT_{seg} is the temperature difference between previous and current segments.

The electrical resistivity is also calculated by using a quadratic fourth order equation in Eq. 5-3 and Eq. 5-4 for p and n pellets.

$$\begin{aligned} \rho_{n_i} = & \rho_{coef1_n} + \rho_{coef2_n} T_{avg_i} + \rho_{coef3_n} T_{avg_i}^2 + \rho_{coef4_n} T_{avg_i}^3 + \\ & \rho_{coef5_n} T_{avg_i}^4 \end{aligned} \quad (5-5)$$

$$\begin{aligned} \rho_{p_i} = & \rho_{coef1_p} + \rho_{coef2_p} T_{avg_i} + \rho_{coef3_p} T_{avg_i}^2 + \rho_{coef4_p} T_{avg_i}^3 + \\ & \rho_{coef5_p} T_{avg_i}^4 \end{aligned} \quad (5-6)$$

The internal resistance for each segment is calculated by applying the electrical resistivity which is given by:

$$R_{seg_{n_i}} = \rho_{n_i} \cdot \frac{l_{seg}}{A}$$

$$R_{seg_{p_i}} = \rho_{p_i} \cdot \frac{l_{seg}}{A}$$

where, l_{seg} is the segment length and A is the area of pellet.

Due to implementation of Eq. (5-5) and Eq. (5-6) the change of the electrical resistivity value of the TE module in transient mode is illustrated in Fig 5.2.

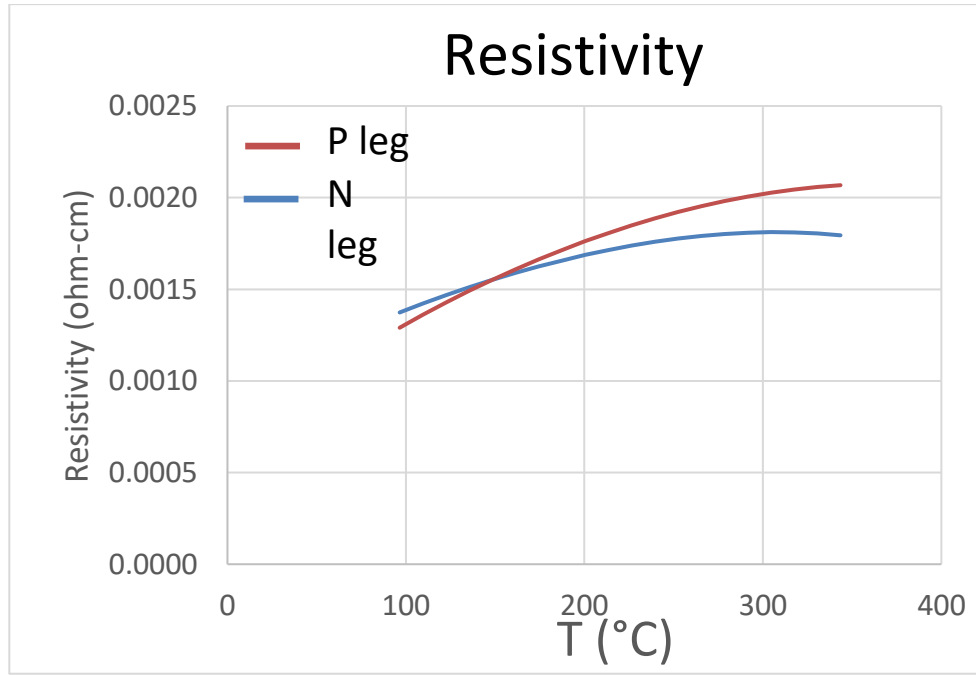


Figure 5-2 Electrical resistivity values of p and n pellets.

The thermal conductivity for each segment is calculated in Eq. (5-7) and Eq. (5-8):

$$k_{n,i} = k_{coef1_n} + k_{coef2_n}T_{avg,i} + k_{coef3_n}T_{avg,i}^2 + k_{coef4_n}T_{avg,i}^3 + k_{coef5_n}T_{avg,i}^4 \quad (5-7)$$

$$k_{p,i} = k_{coef1_p} + k_{coef2_p}T_{avg,i} + k_{coef3_p}T_{avg,i}^2 + k_{coef4_p}T_{avg,i}^3 + k_{coef5_p}T_{avg,i}^4 \quad (5-8)$$

Within the implementation of Eq. (5-7) and Eq. (5-8) the change of the thermal conductivity values in transient mode is illustrated in Fig 5.3.

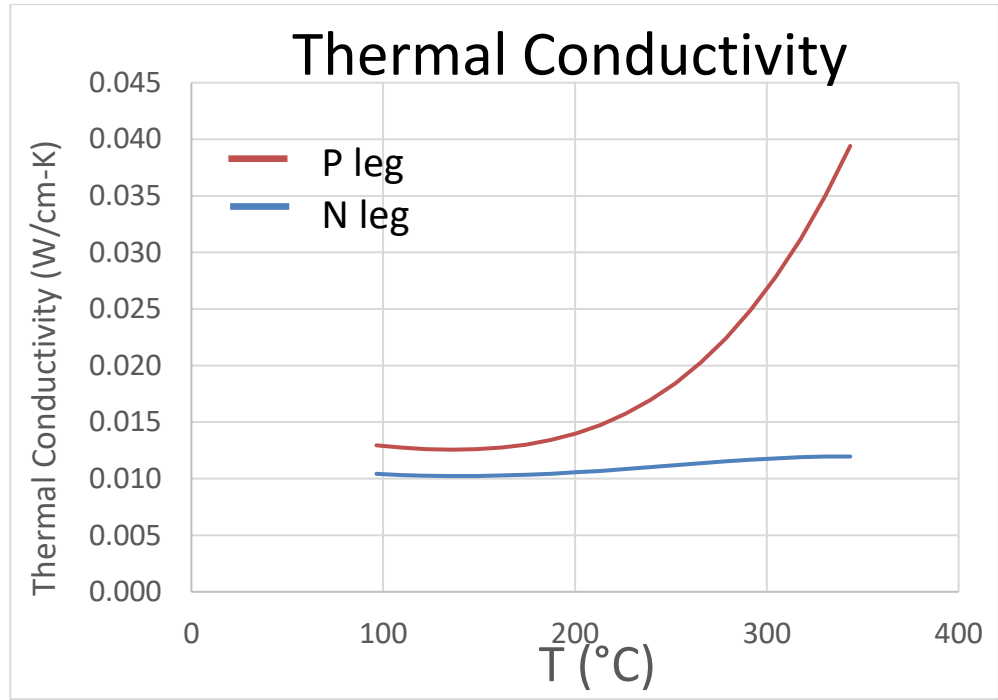


Figure 5-3 TE module thermal conductivity in transient mode.

To obtain the total Seebeck coefficient of one leg, the average value of all the segments is calculated, the same operation is likewise applied for the thermal conductivity which is given by:

$$k_{p,n} = \frac{1}{i} \sum_1^i k_{p,n_i} \quad (5-9)$$

$$\alpha_{p,n} = \frac{1}{i} \sum_1^i \alpha_{p,n_i} \quad (5-10)$$

Within the implementation of the TE module characteristic, the change of the figure of merit (ZT) corresponding to the different temperature values is illustrated in Fig 5.4.

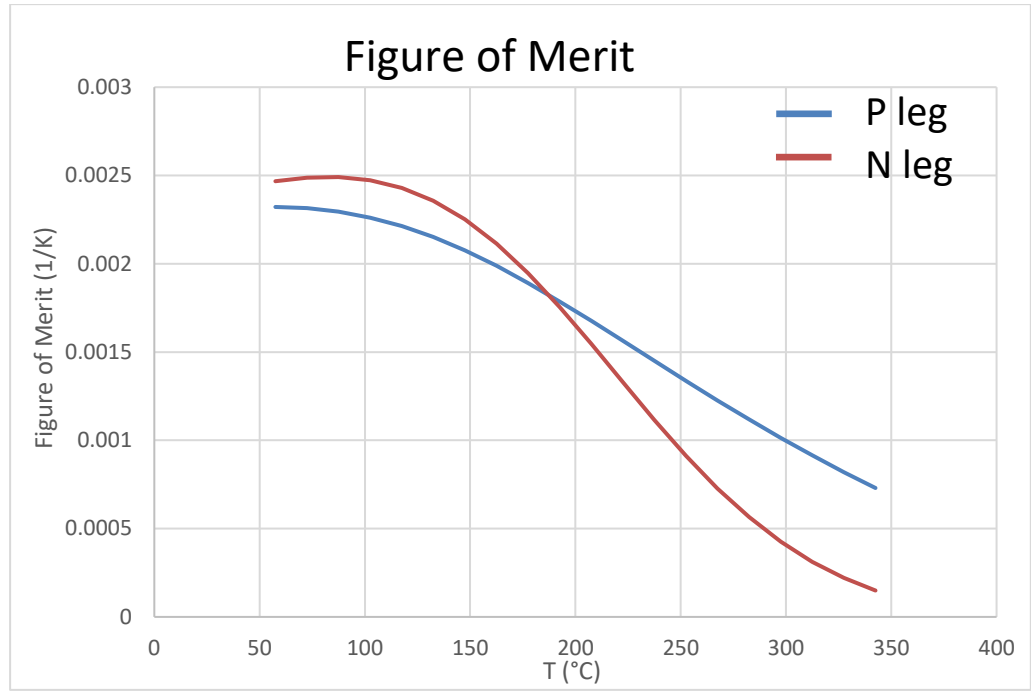


Figure 5-4 TE module figure of merit values.

The voltage and internal resistance values for each leg are calculated by summing the values of each segment which is given by:

$$V_{p,n} = \sum_1^i V_{p,n,i} \quad (5-11)$$

$$R_{in_{p,n}} = \sum_1^i R_{seg_{p,n,i}} \quad (5-12)$$

The connector resistor value R_{conn} is also calculated to obtain the internal resistance of whole module which is given in Eq. (5-15):

$$l_{conn} = \delta_{eggwall} + \phi_{leg_1} \quad (5-13)$$

$$A_{conn} = \phi_{conn} \cdot \delta_{conn} \quad (5-14)$$

$$R_{conn} = \rho_{conn} \cdot \frac{l_{conn}}{A_{conn}} \quad (5-15)$$

where, conn represents the connector and ρ_{conn} is the connector resistivity, ϕ is the width, δ is the thickness, l is the length and A is the area. Consequently, the total internal resistance is illustrated by:

$$R_{in} = n(R_{in,p} + R_{in,n} + R_{conn}) \quad (5-16)$$

where, n is the number of TEM couples.

The power output response for different load resistor values is illustrated in Fig. 5.5.

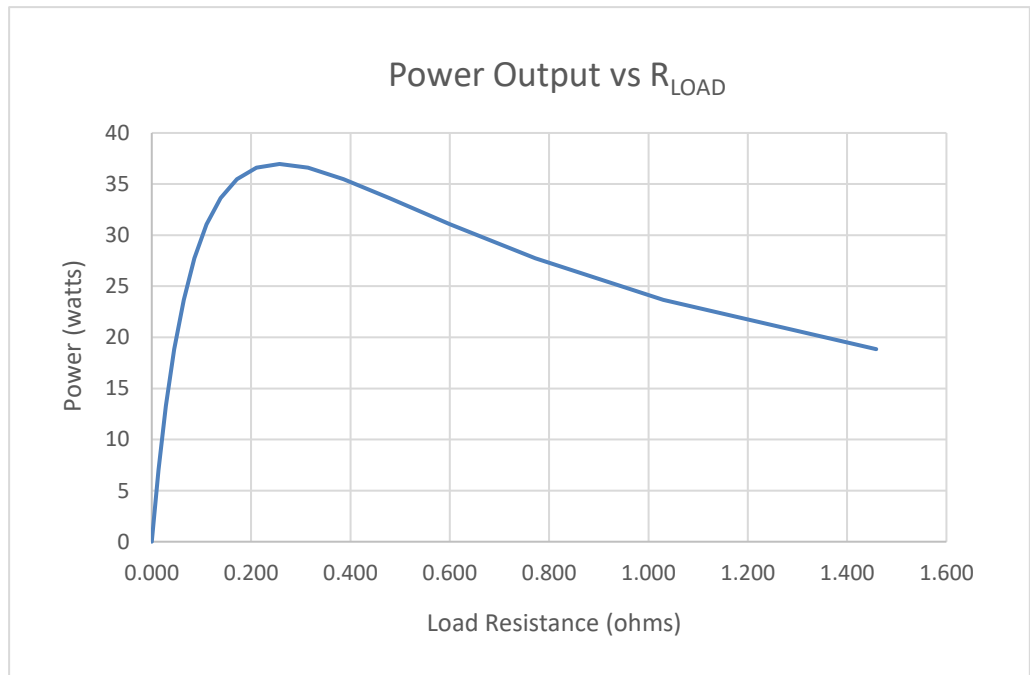


Figure 5-5 TE power output response for different load values.

The open circuit voltage of a TE module is calculated by:

$$E_o = E_{o_coef}n(V_p - V_n) \quad (5-17)$$

where, E_{o_coef} is the open circuit voltage coefficient which represents the power loss in connectors.

The variance of the TE module voltage values corresponding to the TE module current is illustrated in Fig 5.6.

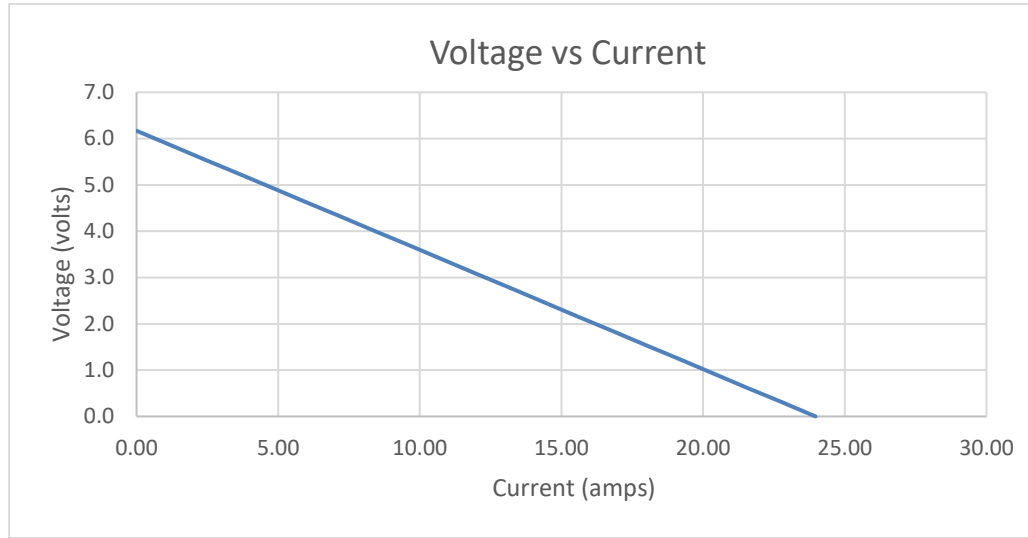


Figure 5-6 TE voltage output according to current output.

The matched load voltage, current and power is given by:

$$V_{load} = \frac{E_o}{2} \quad (5-18)$$

$$I_{load} = \frac{V_{load}}{R_{in}} \quad (5-19)$$

$$P_{load} = \frac{E_o^2}{4R_{in}} \quad (5-20)$$

Within the implementation of Eq. (5-20) the power output and efficiency of the TE module is illustrated with respect to current in Fig 5.7.

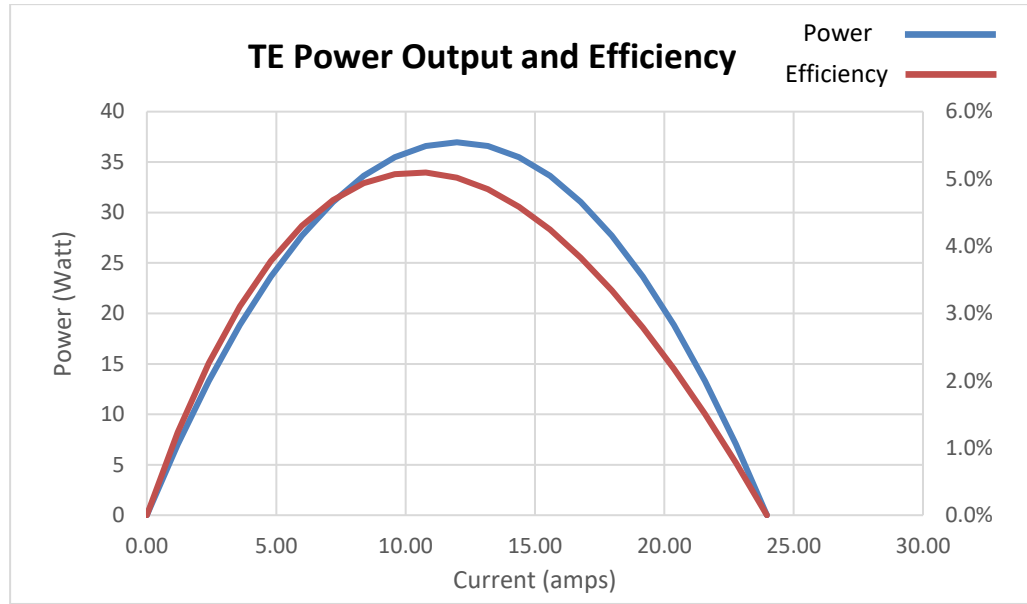


Figure 5-7 Power output and efficiency of TE module.

5.2 TE Module Heating Energy Simulation

After completing the power generation simulation, the heat energy is analysed in the program to achieve an efficiency, energy loss and heat flux calculation. In this simulation, the ambient temperature is accepted to be constant, contrary to the previous thermal dissipation simulation in chapter 3 because the module used for this simulation is fully isolated so ambient temperature variance is decreased to a negligible condition.

The initial calculation of the coding begins with the lattice energy for each pellet which occurs due to the thermal conductivity. As mentioned by Girard et al. [54], recent researches in thermoelectric systems have shown that implementation of appropriate nanostructures into TE can significantly suppress the lattice thermal

conductivity and therefore enhance ZT . The lattice energy is also known Fourier's law of heat conduction calculation is given by:

$$Q_{latt_{n,p}} = K\Delta T = \frac{k_{n,p}A}{l}\Delta T \quad (5-21)$$

The second section of the thermal energy calculation is the Seebeck energy which is the presence of the Peltier effect. Heat absorption or rejection at two different semiconductors junction occurs due to the Peltier effect, therefore the Seebeck energy calculation is usually examined in the hot side and the cold side separately. For this simulation only the hot side Seebeck energy calculation for each leg is applied into system which is given by:

$$Q_{sbck_{hot_{n,p}}} = \Pi I = (T_{hot} + 273)\alpha_{n,p}I_{n,p} \quad (5-22)$$

The last section of the internal energy calculation is the Joule energy which occurs due to the Thomson coefficient and is given by:

$$Q_{joule_{n,p}} = \frac{1}{2}I^2R_{n,p} \quad (5-23)$$

The total internal energy for each pellet is given by:

$$Q_{in_{n,p}} = Q_{latt_{n,p}} + Q_{sbck_{hot_{n,p}}} - Q_{joule_{n,p}} \quad (5-24)$$

In addition to internal loss, the dissipated heat energy in the eggwall is also calculated as an external loss and is illustrated by:

$$\Phi_{1TEM} = n_{leg_1} \cdot \Phi_{leg_1} + (n_{leg_1} + 1) \cdot \delta_{eggwall} \quad (5-25)$$

$$\Phi_{2TEM} = n_{leg_2} \cdot \Phi_{leg_2} + (n_{leg_2} + 1) \cdot \delta_{eggwall} \quad (5-26)$$

$$A_{eggwall} = (\phi_{1TEM} \cdot \phi_{2TEM}) - n_{leg} \cdot A \quad (5-27)$$

where, $n_{leg_{1,2}}$ is the number of legs at side 1 and side 2, n_{leg} is the total number of legs of the TEM. In addition to this calculation, the eggwall loss energy is given by:

$$Q_{egg} = k_{egg} \Delta T \frac{A_{eggwall}}{l_{eggwall}} \quad (5-28)$$

In light of the calculated energy values, the total heat energy applied to TE module is given by:

$$Q = \frac{n_{leg}}{2} (Q_{in_n} + Q_{in_p}) + Q_{egg} \quad (5-29)$$

Another important parameter, heat flux, can also be obtained by:

$$q = \frac{Q}{\phi_{1TEM} \cdot \phi_{2TEM}} \quad (5-30)$$

Table 5-3 Hi-Z 20 module properties and measurements.

Th=350°C and Tc=50°C		
thickness =	0.57	cm
width 1 =	6.72	cm
width 2 =	6.72	cm
T hot =	350	°C

T cold =	50	°C
# legs =	142	
Eo =	6.169	volts
V* =	3.085	volts
I* =	11.9836	amps
Ri =	0.257	ohms
P* =	36.966160	watts
Q =	776.003	watts
q =	17.1840	W/cm ²
η^* =	4.8%	
η =	5.1%	max

The parameters that were applied into simulation and the output parameters of the TE module simulation are given in Table 5-3.

5.3 Thermoelectric Generator full scale simulation

In this simulation section, the calculated single module was adapted into a full scale test rig to measure the total power generation and the applied heat energy. To increase the accuracy of the results, each layer's temperature gradient is applied into the coding according to a CFD simulation of the actual test rig, which is given in chapter 7.

Initially, the first heating plate in the system is assumed to be at 350°C and the cooling plate of the test rig is applied as 90°C. This temperature value is decided according to the radiator temperature of the automotive system, which is considered to integrate with the TEG cooling exchange system in a practical application.

In the second section of the full scale simulation, the ADVISOR software program which provides actual exhaust system parameters of a chosen driving cycle is used to obtain the exhaust gas temperature values at the catalyser section. In this section, the hot side temperatures are converted to a variable parameter in consideration of the new European driving cycle (NEDC) which provides thermal parameters of automotive parts during drive on road are illustrated in Fig. 5.8, Fig. 5.9 and Fig. 5.10.

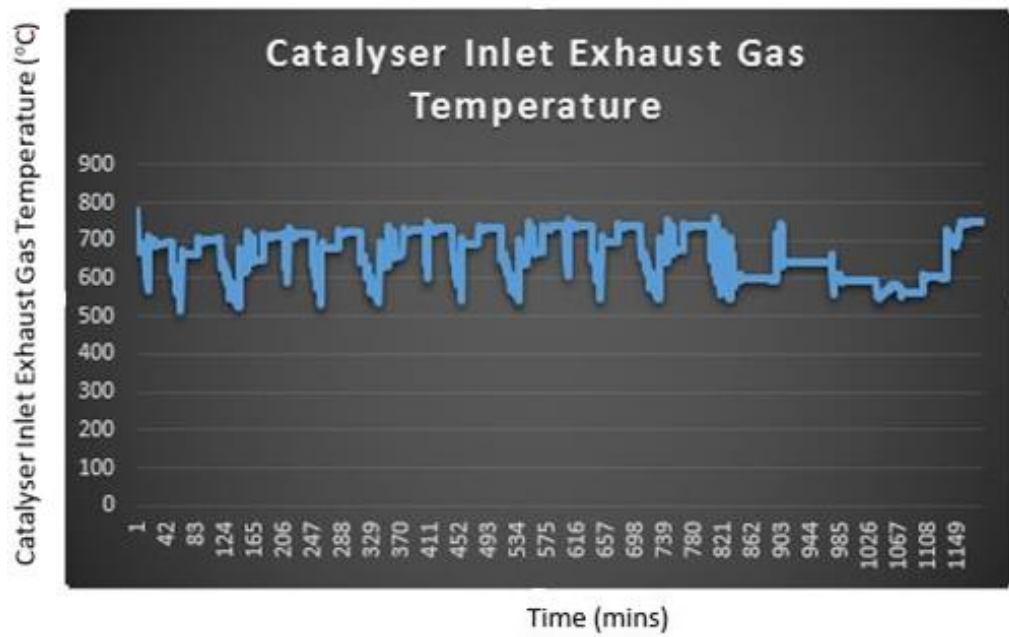


Figure 5-8 ADVISOR catalytic converter inlet exhaust gas temperature (K) during NEDC.

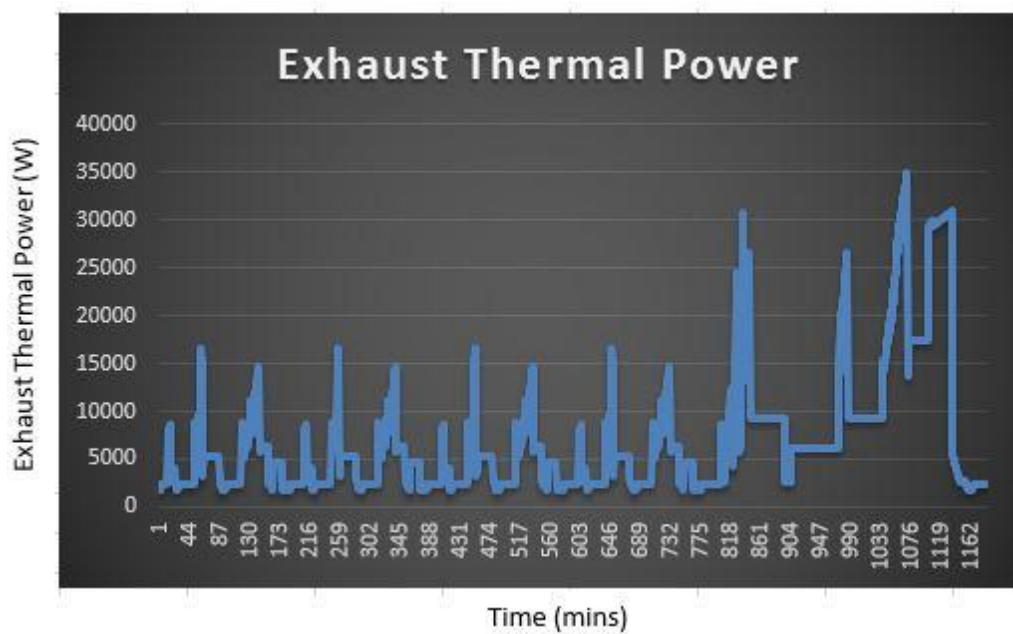


Figure 5-9 ADVISOR exhaust Thermal Power values during NEDC.

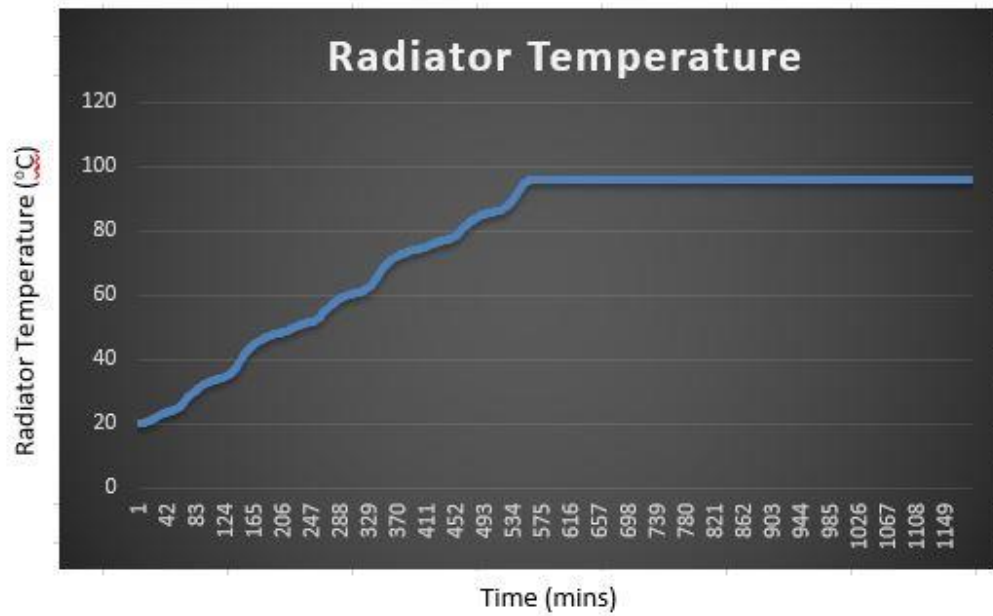


Figure 5-10 ADVISOR radiator temperature values during NEDC.

5.3.1 TEG Simulation Results

In this TEG simulation design, initially a 350°C hot side temperature and a 90°C cold side temperature is applied to the first module of the TEG. The following modules are operated within a 2°C decrement at each module on the hot side block while the cold side block temperature is held at 90°C. This temperature implement system is calculated according to the CFD simulation of the TEG unit which is given in chapter 7. The individual TE module's electrical output data is illustrated in Fig 5.11.

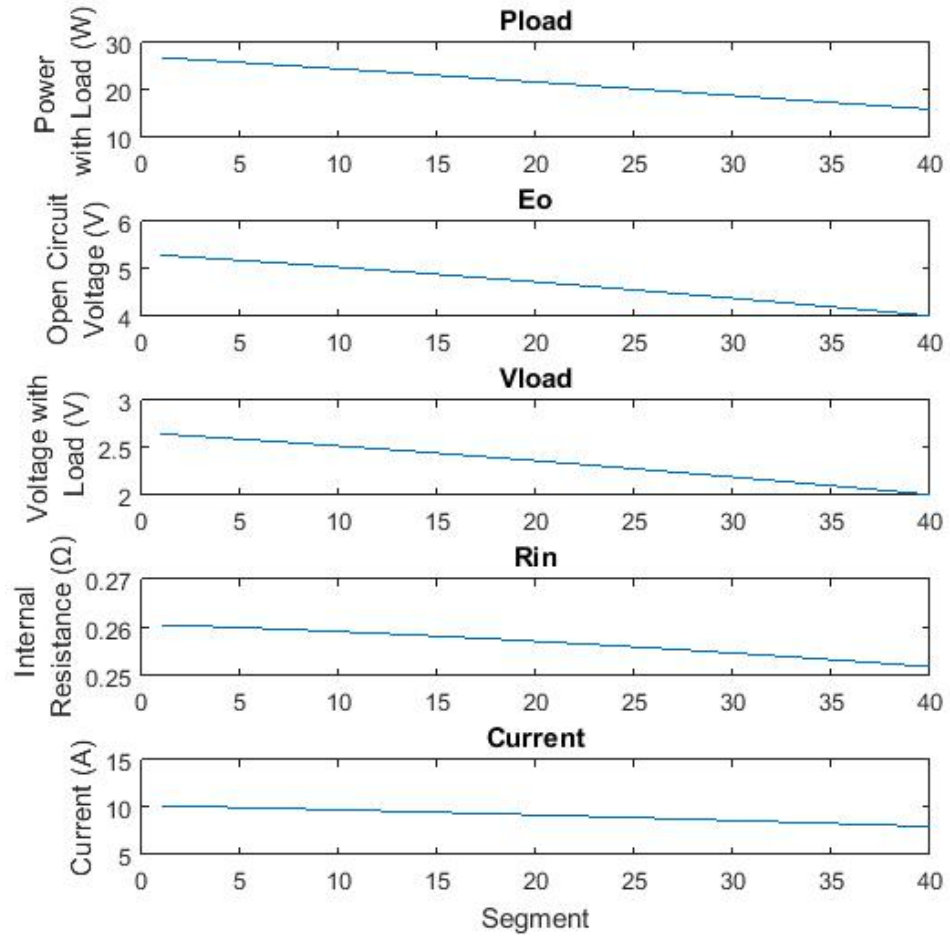


Figure 5-11 TE generator electrical outputs at each segment.

As observed from Fig 5.11 the electrical outputs decrease corresponding to the temperature gradient decrement, which occurs due to the previous TE modules electrical power generation and thermal power absorption. According to the simulation results, the variance of electrical outputs between the first and last module of the TEG is given in Table 5-4.

Table 5-4 Electrical outputs of first and last TE modules

	P_{LOAD}	V_{OC}	V_{LOAD}	I_{LOAD}	R_{IN}
First TE	26.1W	5.3V	2.6V	9.86A	0.268Ω

Last TE	15.5W	3.975V	2V	7.8A	0.255Ω
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In addition to the electrical outputs, the thermal power input is also simulated to observe the efficiency and the requirements of the system. The individual TE modules thermal input power data is illustrated in Fig 5.12.

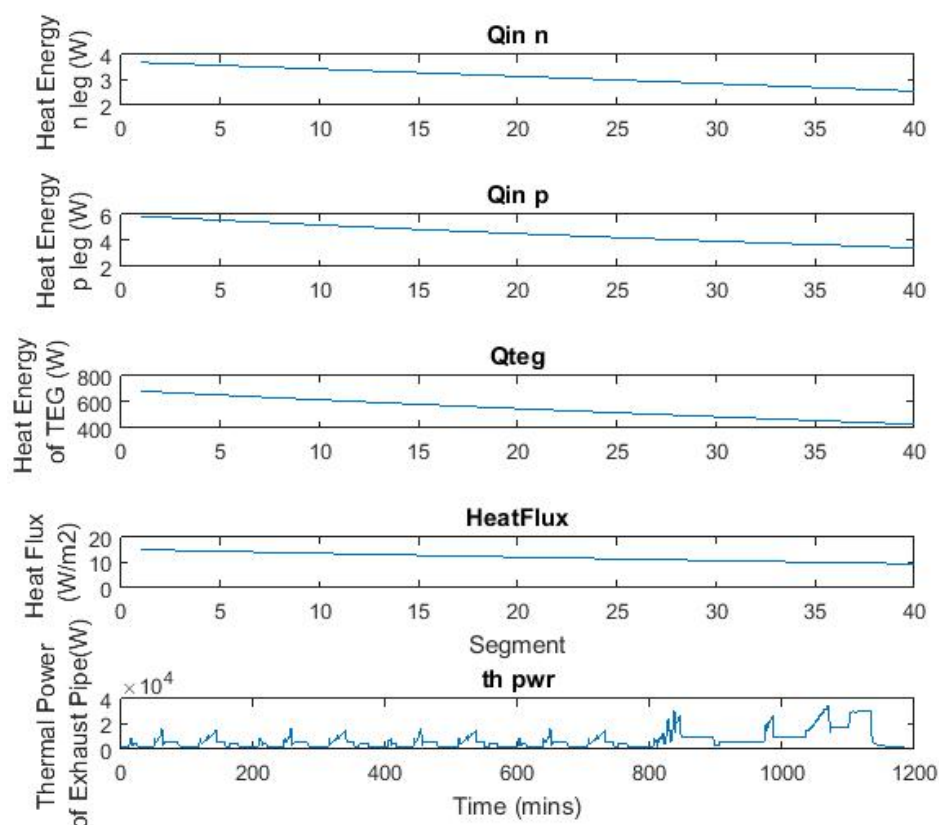


Figure 5-12 TE generator thermal power inputs at each segment.

As observed from Fig 5.12, the applied thermal power decreases through the TEG segments, which is also a reason for the power output decrease. In the first two plots, each pellet's thermal power input is illustrated and it is observed that p type pellet requires more thermal power than the n type pellet. Each pellets thermal power requirement for power generation consists of a lattice and the

Seebeck thermal power, therefore the difference of Q_{in} values can be explained by a lattice thermal power because the Seebeck thermal power variance between pellets is not high enough to cause this difference. The reason for a lattice thermal power variance is the thermal conductivity values of pellets, p type materials have a higher thermal conductivity than n type materials. The last plot of Fig 5.12 is obtained through the ADVISOR software which provides the actual thermal power of automotive exhaust system corresponding to an NEDC driving cycle.

Table 5-5 Total electrical and thermal output of large scale TEG simulation.

Pload(W)	Rin	Vo	Vload	Current
861.09298	10.27031275	187.61	93.805	365.0829
Eff	Qin_n	Qin_p	Qteg	Heat Flux
0.039184	125.0645	182.224	21975.46	486.6307

As observed from Table 5-5, the overall efficiency of a large scale TEG is around 4% within the 21975 W thermal input and 861W power output range. When all the TE modules are connected in parallel, the total expected current output is 365 A. In addition, when all the TE modules are connected in series, the expected open circuit voltage value is 187.61 V. The increment of efficiency can be obtained by setting the TEG voltage output to 48 V therefore a connection of two rows in parallel with the first 19 and last 21 modules in series provides a better performance than other configurations. In this configuration, the expected output voltages of rows are respectively 47.8 V and 46 V.

5.4 H-Bridge Converter Simulation

The H-Bridge converter simulation is designed to understand the transient and steady state responses of the power converter. A basic H-Bridge design is applied into the system to compare the H-Bridge converter with other converter methodologies. In addition to converter comparisons, the effect of component values is also simulated to observe the settling time, overshoot and other converter characteristics.

5.4.1 H-Bridge Converter Simulation Design

In this section, a full bridge DC-DC converter is assembled within the converter and controller units as shown in Fig 5.13. The converter unit consists of four MOSFETs, an inductor and capacitance. Additionally, an LC filter and a load resistor are applied into system. The controller unit consists of a transfer function unit which determines the duty cycle, a PWM generator and a switch controller which determines the converter modes of buck and boost.

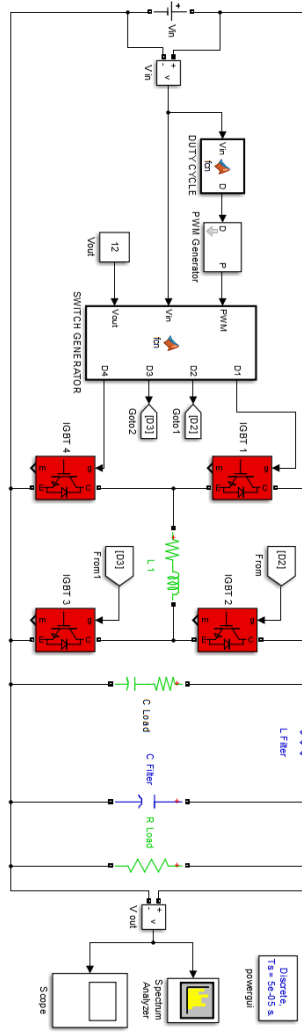


Figure 5-13 H-Bridge Converter Simulation Design.

To understand the effect of capacitance and inductor values the H-Bridge converter is simulated with different component values. The inductor and capacitance components are set to high and low value. LC, HC, LL, HL represent low value capacitance, high value capacitance, low value inductor and high value inductor respectively.

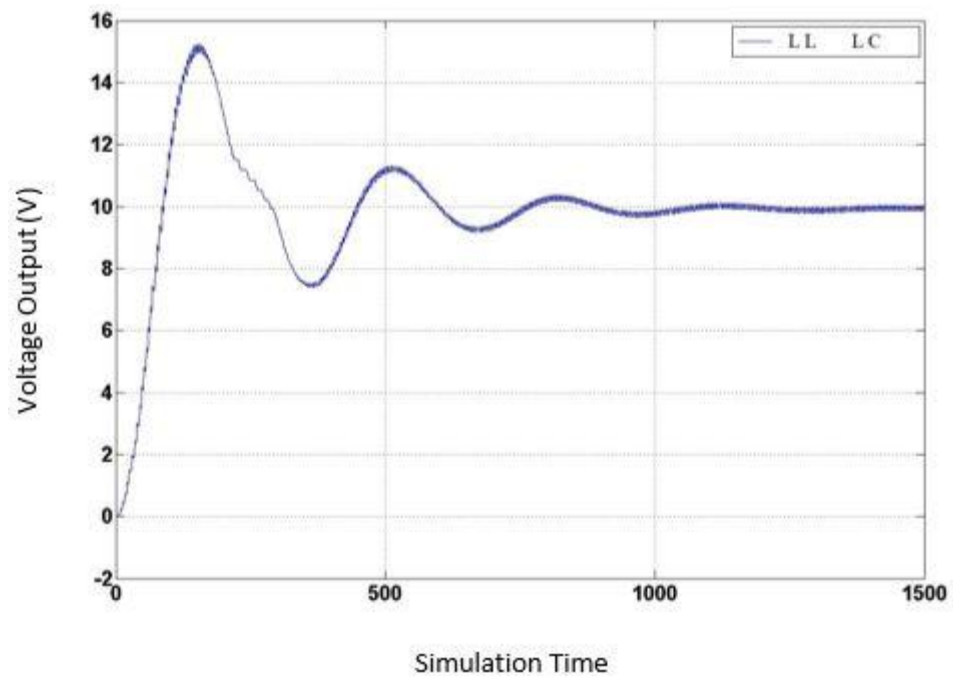


Figure 5-14 Voltage output at low value inductor and capacitor.

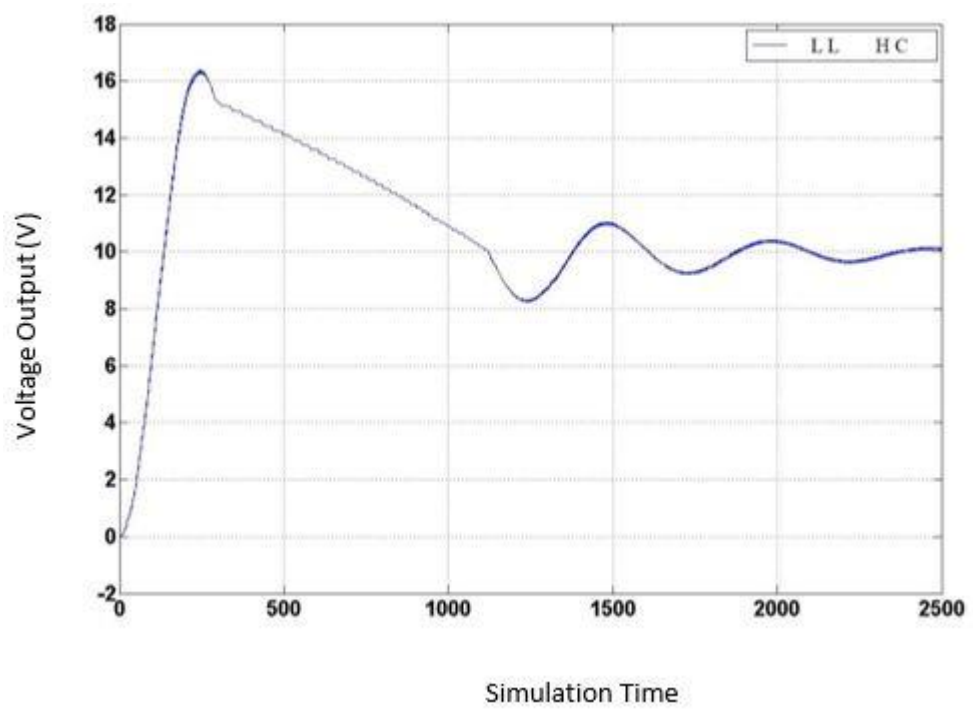


Figure 5-15 Voltage output at low value inductor and high value capacitor.

Within the comparison of Fig 5.14 and Fig 5.15, an increase of the capacitor value provides less voltage ripple however it increases the overshoot value and the settling time of voltage output signal.

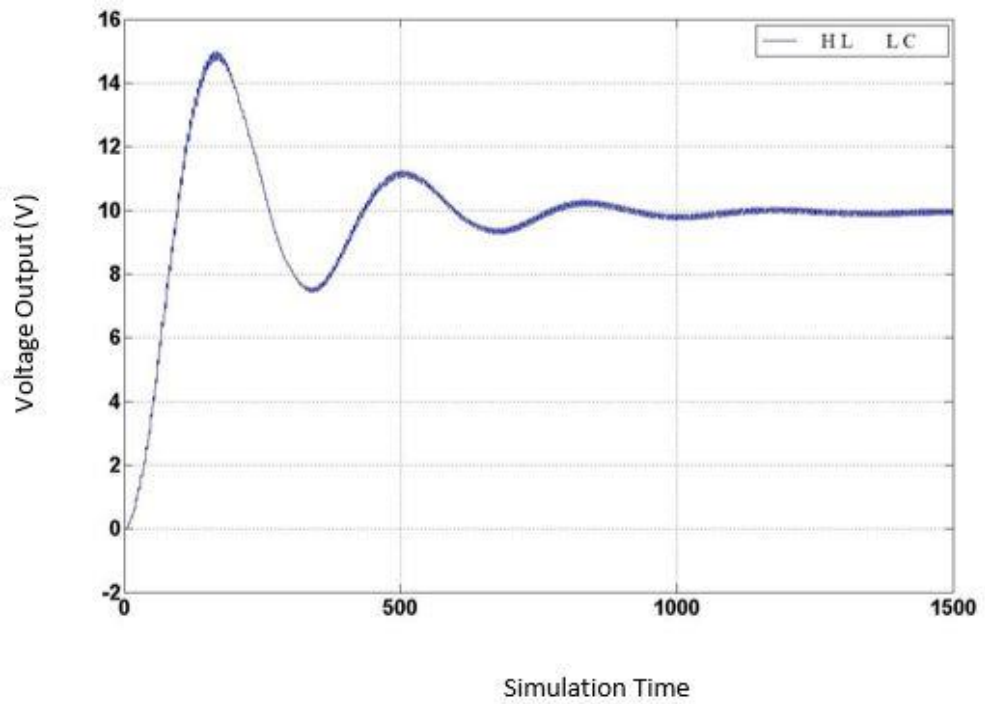


Figure 5-16 Voltage output at high value inductor and low value capacitor

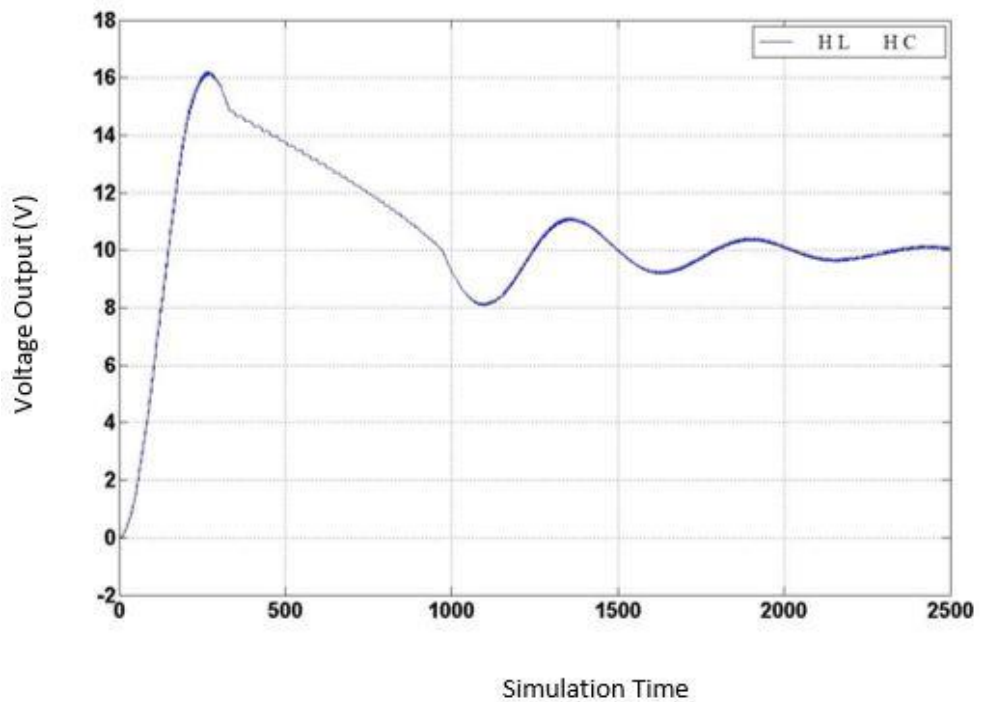


Figure 5-17 Voltage output at high value inductor and capacitor.

Within the comparison of Fig 5.14 and 5.16, an increase of the inductor value can provide less ripple at output voltage due to a decrease in the current ripple. In low power applications, using a low value inductor is an option especially at the DCM condition. However, in high power applications this causes a high power loss due to requirement of the CCM operating condition.

The voltage output is filtered by the designed Chebyshev filter corresponding to the transfer function of the H-Bridge converter. A low pass Chebyshev filter is applied to eliminate AC current in the system to improve efficiency. A comparison of the non-filtered and Chebyshev filter voltage output is illustrated in Fig 5.18.

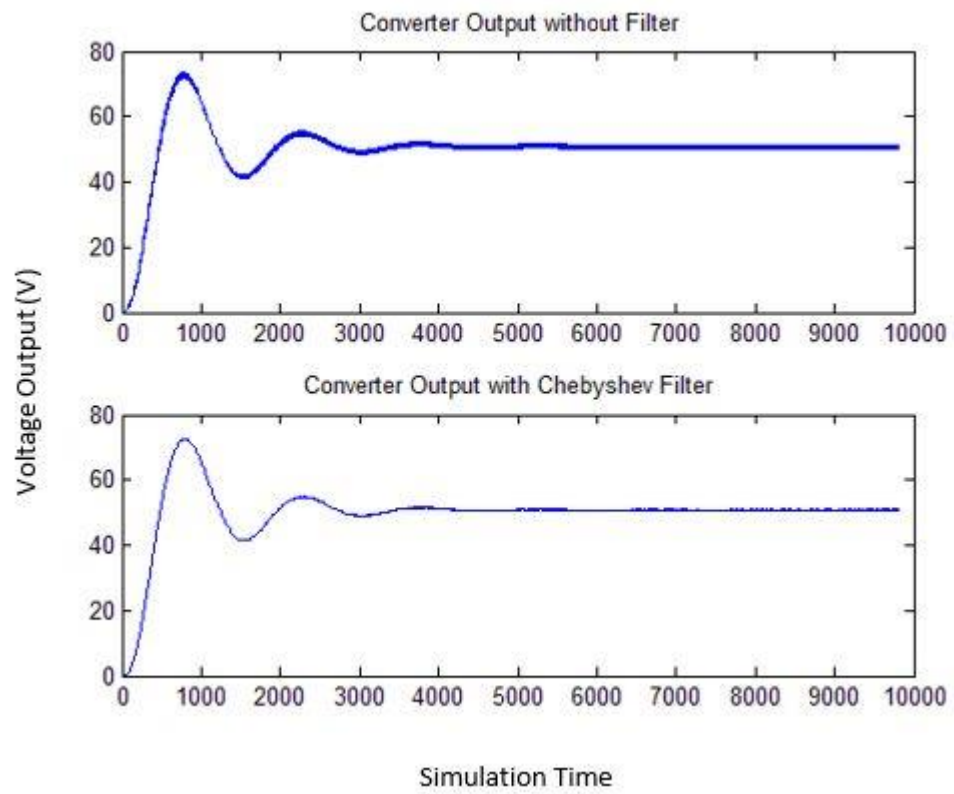


Figure 5-18 Designed Chebyshev filter voltage output.

Chapter 6 H-Bridge DC-DC Converter Design

6.1 H-Bridge DC-DC Converter Principles

Most of the batteries applied into automotive systems have an inconstant voltage value which is tuned corresponding to the level of its charging mode. Due to this variation efficiency becomes dependent on charging voltage value. The TE generator without a converter has a low efficiency as a charging system, even though its voltage output is higher than the battery voltage, as stated in the literature review. However, a converter system with a MPPT has 34% more efficiency than without a controller system. Converter systems are generally controlled with two operating methods, one of them is the PWM controller and the second one is a MPPT controller. A PWM controller provides a constant voltage at the output which is slightly higher than the battery voltage while a MPPT controller output varies according to the charging state of the battery. Due to this variation, the MPPT controller can obtain higher efficiency than the PWM.

Variable sources, which are mostly found in renewable energy systems, require a power converter with both the ability to step up and step down. There are several DC-DC converters which can charge a battery at demanding level as explained in chapter 4. The H-Bridge DC-DC converter, which has the ability to buck and boost the input voltage without inverting, is adequate for renewable energy systems. The advantages of H-Bridge converter over other converters are:

- Having a bi-directional operating system which can charge and discharge a battery
- Requirement of a single inductor rather than a couple as in the SEPIC and Zeta converter
- Having two PWM signals which can operate the buck and boost side converters with a different duty cycle.

The H-Bridge DC-DC converter comprises of step-down and step-up segments and is mainly operated by the feedback to the step down and step up segments themselves, corresponding to the statement of the transfer function. In PWM systems, the buck-boost converter requires a phase regulation of the feedback operator which controls both step up and down conditions. Furthermore, during the mode change from step up to step down or vice versa, corresponding to a variance in the input voltage, a high transient voltage is applied to the output voltage. In this project, the applied undesired transient voltage is decreased by a feedforward from the input side to react to a change in the supply voltage rapidly then reach the maximum power point. This MPPT controller system provides steadiness over a variant input voltage with a high efficiency by performing a supply feedforward operation.

First of all, the main process and power converter steady state features are examined. A decrease in the conduction losses by a supply side feedforward operation is introduced within the investigation of the results. In addition to the decrease of conduction losses, the feedforward operation method also provides a smoother transition for the buck and boost mode changes for the supply side

variances. Additionally, the use of two PWM signals at two different frequencies in the step up and step down segments is examined to reduce the switching losses.

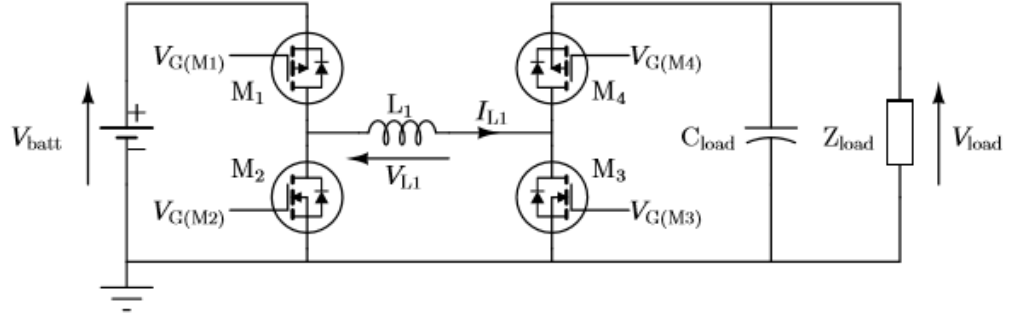


Figure 6-1 Main H-Bridge DC-DC converter schematic.

6.1.1 H-Bridge DC-DC Converter Conversion Ratio

The conversion factor M is also known as the transfer function of the converter and is the ratio of voltage output by voltage input V_{TEG} . The conversion ratio is a function of the duty cycle D and of the switching signal under consideration the of CCM. To perform a voltage step down statement, the DC-DC converter operates in the Buck mode.

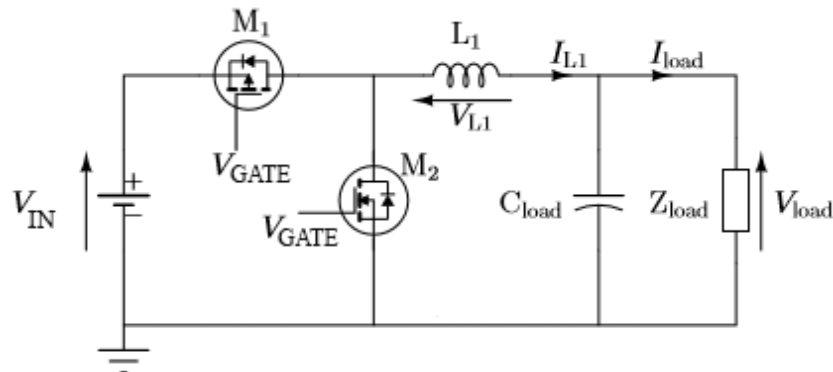


Figure 6-2 Basic Buck Converter Schematic for H-Bridge.

As illustrated in Fig 6.2, the conversion ratio of Buck converter is given by:

$$M_{Buck} = \frac{V_{out}}{V_{in}} = \frac{t_{on}}{t_{sw}} = D \quad (6-1)$$

where, t_{sw} is one period of the signal and t_{on} is the duration of the switched on condition. To perform a voltage step up statement, the DC-DC converter operates in the Boost mode.

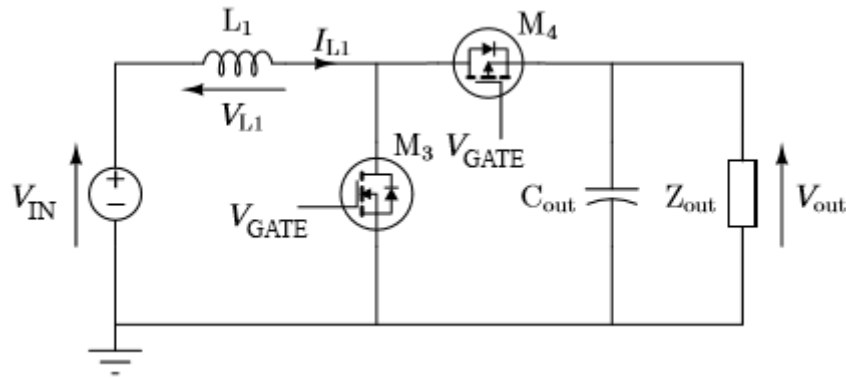


Figure 6-3 Basic Boost Converter Schematic for H-Bridge.

As illustrated in Fig 6.3, the conversion ratio of Boost converter is given by:

$$M_{Boost} = \frac{V_{out}}{V_{in}} = \frac{t_{sw}}{t_{sw} - t_{on}} = \frac{1}{1-D} \quad (6-2)$$

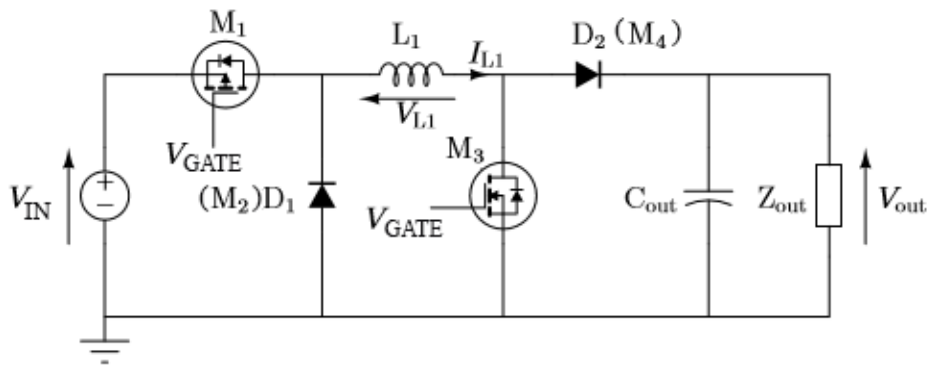


Figure 6-4 H-Bridge Noninverting Buck-Boost Schematic.

When the input voltage approaches the reference voltage output, the converter starts to operate in the Buck-Boost mode. As illustrated in Fig 6.4, the conversion ratio of a noninverting Buck-Boost converter is given by:

$$M_{Buck-Boost} = \frac{V_{out}}{V_{in}} = \frac{t_{on}}{t_{sw}-t_{on}} = \frac{D}{1-D} \quad (6-3)$$

6.1.2 STEADY STATE PERFORMANCE

The H-Bridge converter consists of four transistors, capacitance and an inductor as shown in Fig 6.1. A pair of transistors on the input side act as a Buck converter while the output side pair act as a Boost converter. The buck converter low side and the boost converter high side transistors perform a synchronous regulation while the Buck converter high side and the Boost converter low side performing the switching operation. D1 is a buck converter duty cycle and D2 is a boost converter duty cycle while f1 and f2 are the frequencies of the buck and boost converters, respectively.

The gate signals of the operating transistors, inductor current and capacitor voltage are illustrated in Fig 6.5. The ripple in the output voltage is related to the boost segment transistor. An investigation of the circuit is computed under the same frequency control for both segment converters. A circuit analysis and a mathematical model is illustrated by:

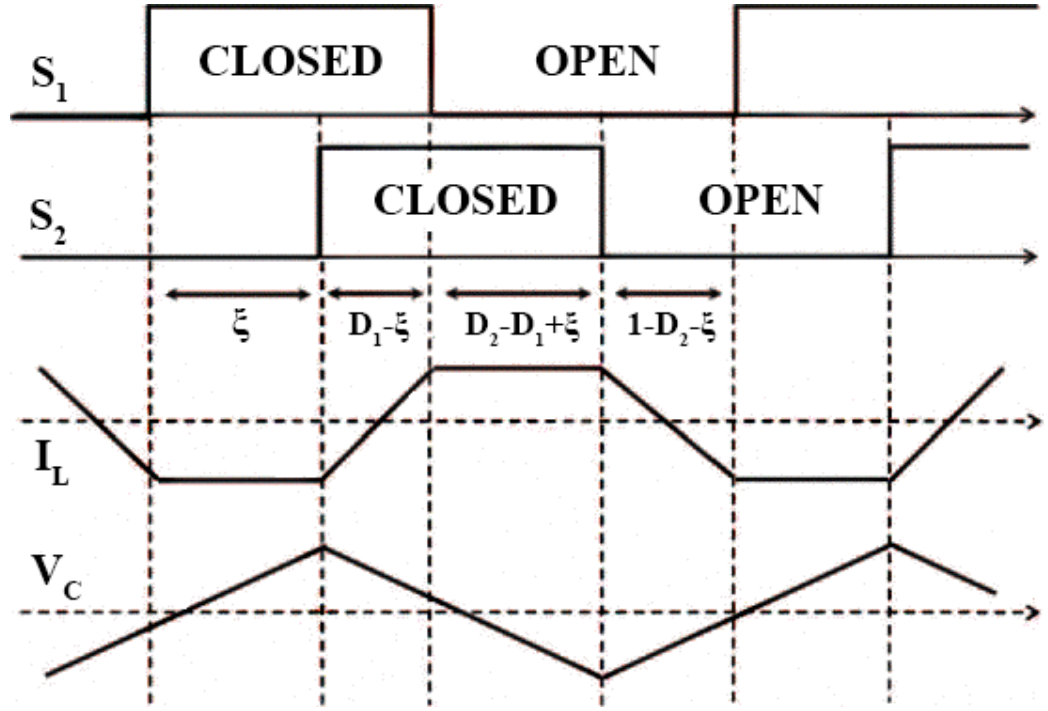


Figure 6-5 PWM control signals, inductor current and capacitor voltage.

$$\frac{di_L}{dt} = \frac{-r}{L} i_L - \frac{(1-D_2) \frac{R}{R+r_C}}{L} V_C + \frac{D_1}{L} V_{IN} \quad (6-4)$$

$$\frac{dV_C}{dt} = \frac{(1-D_2) \frac{R}{R+r_C}}{C} i_L - \frac{V_C}{C} \frac{1}{R+r_C} + \frac{D_1}{L} V_{IN} \quad (6-5)$$

$$V_{OUT} = (1 - D_2) \frac{Rr_C}{R+r_C} i_L + \frac{V_C R}{R+r_C} \quad (6-6)$$

r is the total resistance while charging the capacitor therefore r is:

$$r = 2r_S + r_L + (1 - D_2) \frac{Rr_C}{R+r_C} \quad (6-7)$$

where, r_S is the transistor 'on' resistance, r_L is the inductor resistance and r_C is the ESR of the capacitance. The output dc impedance is illustrated by:

$$Z_o = \frac{r}{(1-D_2)^2} \frac{R+r_C}{R} \quad (6-8)$$

In addition, the conversion ratio of the boost converter when the internal resistors are neglected is illustrated by:

$$M = \frac{V_{OUT}}{V_{IN}} = \frac{D_1}{1-D_2} \quad (6-9)$$

In Fig 6.5, the inductor current i_L represents an ideal current, but in practice the inductor current at S1 and phased S2 is shown in Fig 6.6.

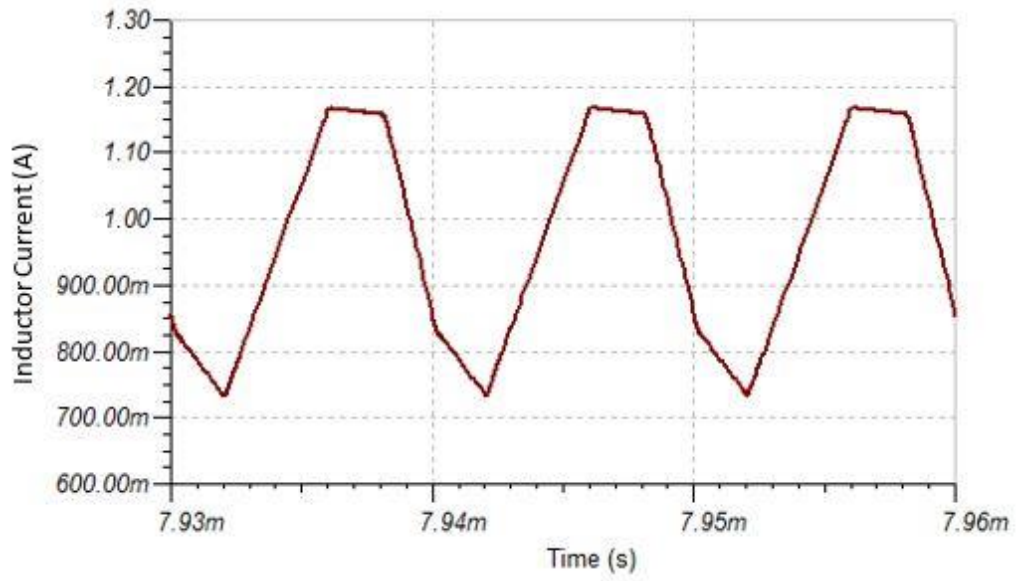


Figure 6-6 Actual inductor current during H-Bridge conversion when phase applied between S1 and S2.

6.1.3 STEADY STATE CHARACTERISTICS

The converter power losses are generally caused by to conduction or switching losses. Z_o varies corresponding to the conduction loss, and enlarges with the boost segment duty cycle D_2 which is derived from Eq. (6-8).

The conduction loss which is a function of the boost segment duty cycle according to Eq. (6-8) increases within the D_2 increment. The conduction loss

decrement is achieved by decreasing D2 contrary to SEPIC and other one signal control systems. As given in the conversion ratio of Boost converter Eq. (6-9), the output voltage is related with both the buck and boost duty ratios separately. This flexibility provides a voltage rectification for the step down operation with the buck segment controller while altering the boost segment duty ratio. To decrease fluctuation during a mode change, from buck to boost or vice versa, the boost segment duty cycle is altered to match the boundary conditions, after which it goes into the transient condition with MPP tracking. The efficiency of the converter can be increased by keeping the boost segment duty cycle lower when the buck duty cycle is maintained constant and high. This approach is demonstrated by the SEPIC and H-Bridge converters comparison.

The conversion ratio of SEPIC and H-Bridge converters are given by:

$$M_{SEPIC} = \frac{V_{OUT}}{V_{IN}} = \frac{D}{1-D} \quad (6-10)$$

$$M_{H-BRIDGE} = \frac{V_{OUT}}{V_{IN}} = \frac{D_1}{1-D_2} \quad (6-11)$$

In the first comparison, the H-Bridge converter D_2 value and the SEPIC converter D value are set to equal amount which is $D = D_2 = 2/3$ and D_1 is set to 1. The conversion ratios are calculated as follow:

$$M_{SEPIC} = \frac{D}{1-D} = \frac{2/3}{1-2/3} = 2$$

$$M_{H-BRIDGE} = \frac{D_1}{1-D_2} = \frac{1}{1-2/3} = 3$$

The output voltage of the two converters when a 12V input voltage applied into the converters is illustrated in Fig 6.7.

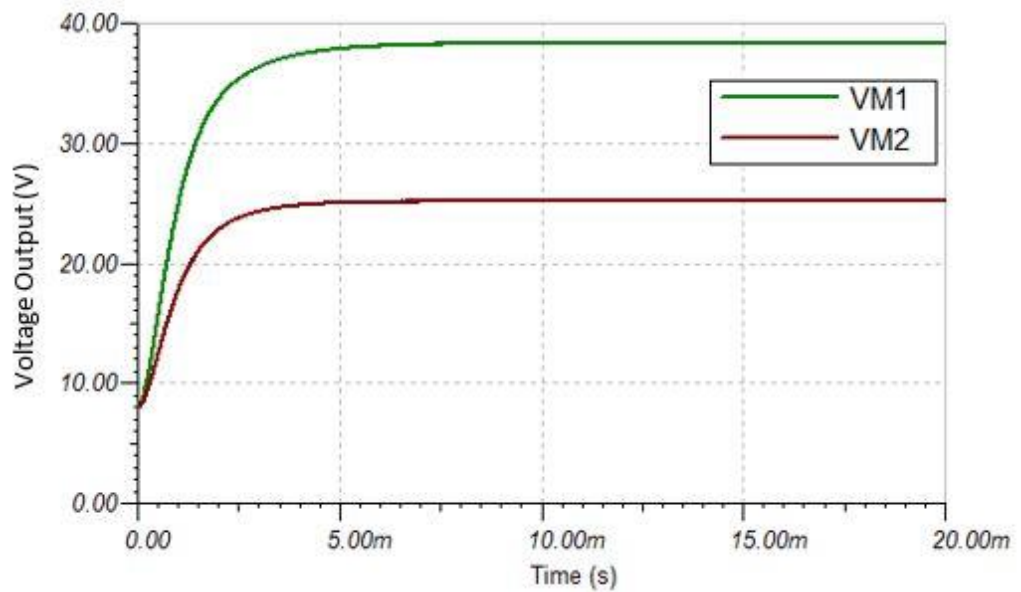


Figure 6-7 SEPIC and H-Bridge output voltage when $D = D_2 = 2/3$.

In Fig. 6.7, VM1 represents the H-Bridge output voltage and VM2 represents the SEPIC output voltage. As observed from Fig 6.7 the SEPIC converter has a lower output voltage value than the H-Bridge converter at the same value of D and D_2 and similarly at the same conversion ratio value $D_2 < D$. As explained in the steady state characteristics, a low D_2 value provides less power loss and a higher efficiency.

In a second comparison of the SEPIC and H-Bridge converters, which is illustrated in Fig 6.8, both inductor currents are kept the same and the obtained H-Bridge output voltage is higher than the SEPIC output voltage, therefore it can be derived that the H-Bridge power output is higher than the SEPIC power output and the H-Bridge efficiency is higher than the SEPIC efficiency.

Both these comparisons show that two separate duty cycle operation system, which is applied into the H-Bridge converter, have better performance than single duty cycle operation systems.

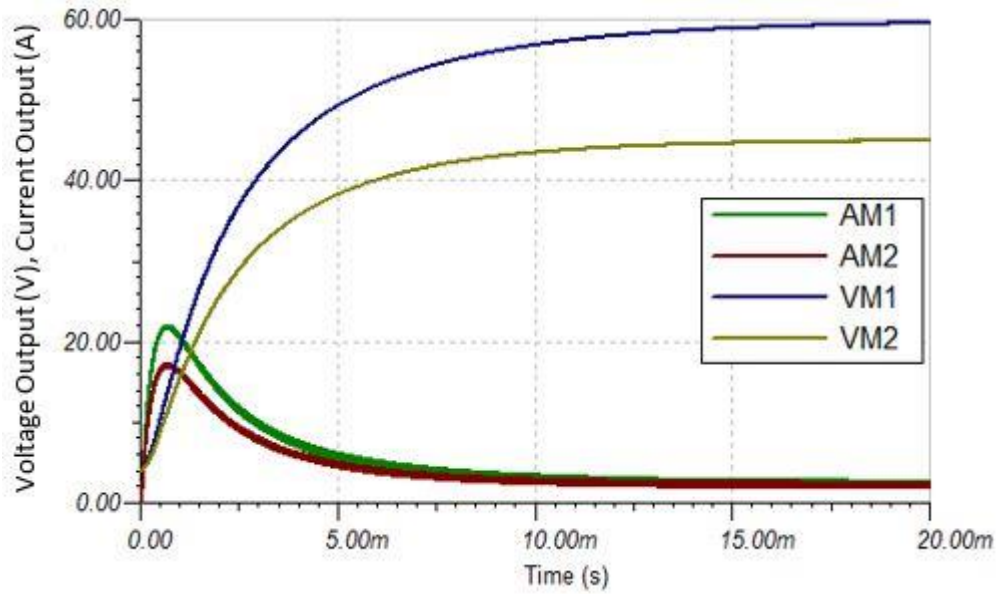


Figure 6-8 H-Bridge and SEPIC converter`s voltage and current output.

6.2 H-Bridge Power Converter Design

To obtain the required current rating, parallel connected transistors are required, as illustrated in Fig 6.9. A couple of MOSFETs are applied into system for the high and low side switching in the H-Bridge DC-DC converter, cascaded transistors decrease demand on the current rating of each component hence the conjunction heating.

In Fig 6.9, the converter input is connected to the TE generator terminals in parallel within the couple of $1\mu\text{F}$ 100V rating capacitors which provide a filter unit in the input side of the converter to maintain an enhanced signal. In addition, in dc operation the inductor behaves as a current shunt due to its characteristics, therefore the supply current measurement is achieved across a couple of resistors, which are placed after the inductor.

In the following side of the converter, the transistors are illustrated in full bridge mode. The high and low side components are connected in parallel where A, B, C, D determines the transistors driving signals. The switching transistors are protected by a 20V Zener diode which provides a Zener effect over 20V at the transistor gate.

The last segment of the H-Bridge is the output section which consists of capacitors and parallel connected resistors. A high value capacitor is applied into the system as a dc link capacitance and other low value capacitors provide an output filter by behaving as a decoupling capacitor. In addition, the parallel connected shunt resistors provide a current measurement in the output section.

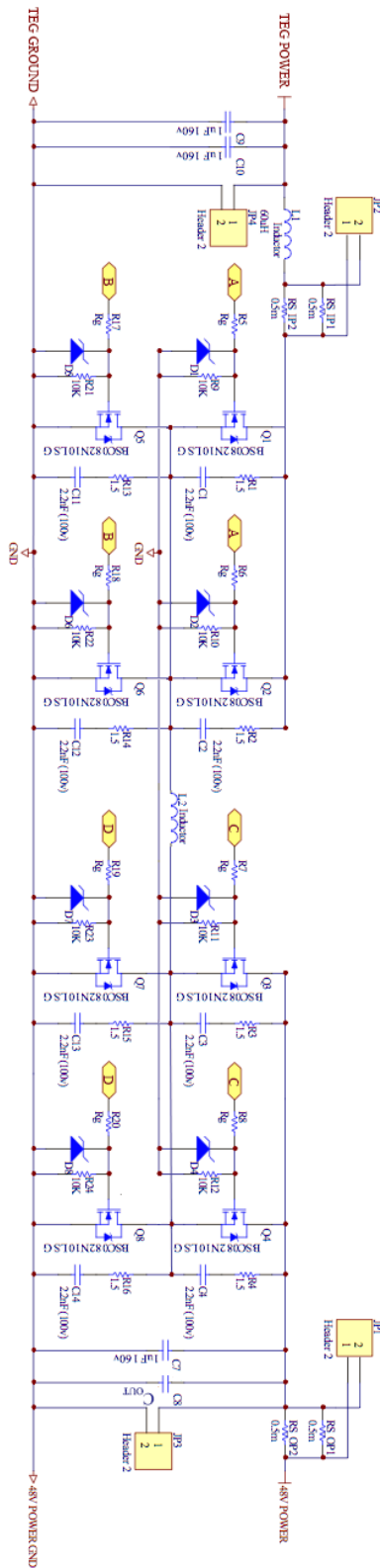


Figure 6-9 Schematic diagram of built H-Bridge DC-DC converter.

6.2.1 PWM Transmitting and Protection Circuit

A fibre optic connector is applied into the system between the pulse generator circuit and the main circuit to obtain a signal transmission of up to 100 kHz PWM signal. In addition, to install a buffer, a small power DC-DC converter and optic connections between the gate-driving signal source and the high power DC-DC converter MOSFETs is essential to protect pulse generator, due to a vulnerability to high current and voltage in the microcontroller unit.

The diagram of transmitting and protection circuit is illustrated by:

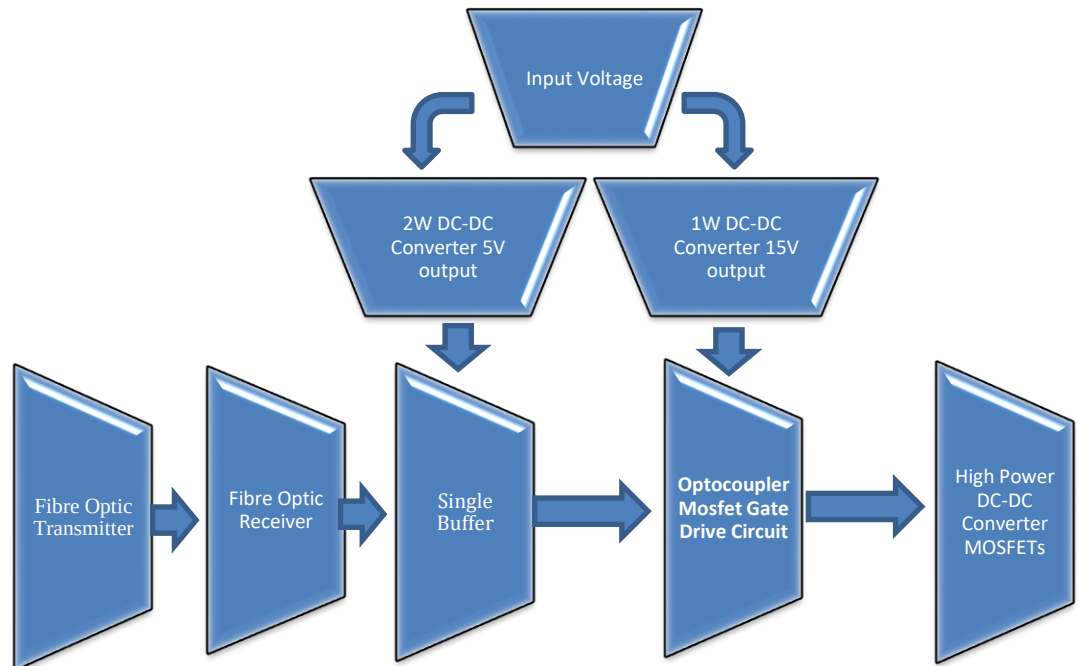


Figure 6-10 Diagram of circuits between pulse generator and MOSFETs.

6.2.1.1 Fibre Optic Transmitter and Receiver

A 5 MBd Link HFBR-15X1Z optic transmitter and a HFBR-25X1Z optic receiver is used to provide communication between the signal generator and the

H-Bridge DC-DC converter up to 100 kHz. A versatile fibre optic connector's receiver unit includes a monolithic DC coupled, a digital IC receiver with an open collector Schottky output transistor and an internal pullup resistor [58]. A disadvantage of using a fibre optic connection is the incurred propagation delay, which is typically 5 ns in a one metre cable.

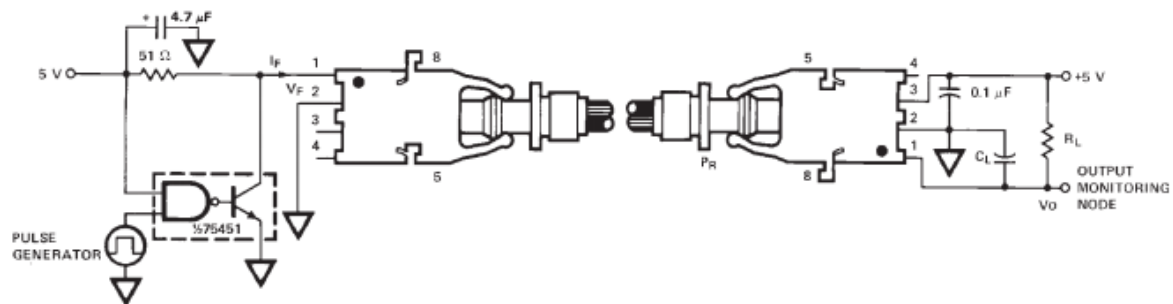


Figure 6-11 Applied transmitting and receiving circuits. [58]

6.2.1.2 Single Inverter Buffer/Driver

A buffer circuit SN74LVC1G06 with an open drain output, which is shown in Fig. 6.12, is applied into the system to protect the PWM receiver component. Despite its appearance that it only duplicates input at output, the buffer also provides a solution for impedance issues amongst the two circuits. This device is fully specified for partial-power-down using I_{off} . The I_{off} circuitry disables the outputs, preventing damaging current backflow through the device when it is powered down [57]. A bypass capacitor is applied into the supply voltage side to prevent power disturbance.

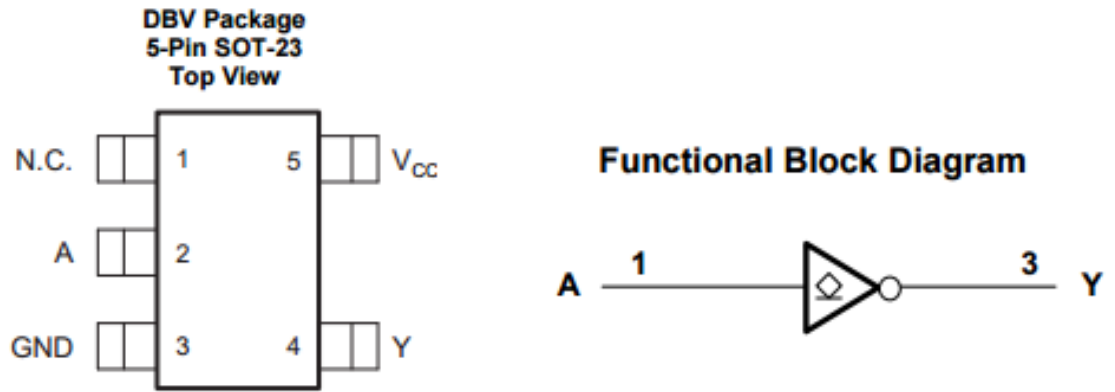


Figure 6-12 Buffer Physical and Logic Model. [57]

6.2.1.3 Optocoupler MOSFET Gate Drive

A decrease in the R_g value can prevent the requirement of a negative IGBT gate drive in optocoupler applications as shown in Fig 6.13. However, by using a MOSFET instead of an IGBT, one can eliminate the demand of an R_g decrease.

The minimum R_g calculation is illustrated by:

$$\begin{aligned}
 R_g &\geq \frac{V_{CC} - V_{EE} - V_{OL}}{I_{OL_PEAK}} & (6-12) \\
 &= \frac{15V - 0V - 2V}{2.5A} \\
 &= 5.2\Omega = 6\Omega
 \end{aligned}$$

The minimum R_g value is calculated as 6 Ohms but due to further analysis of Fig 6.13 [59] a higher R_g value is applied into the system to decrease the total power dissipation.

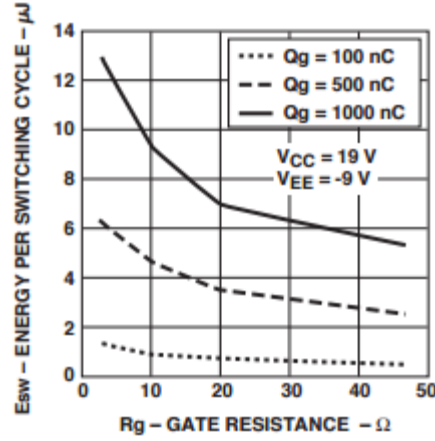


Figure 6-13 Energy dissipated in the HCPL-3120 for each IGBT switching cycle.

[59]

The total power dissipation is a total of the emitter power and the output power. While the emitter power is a function of the duty cycle, the output power is a function of the switching frequency. The power dissipation is illustrated by:

$$P_T = P_E + P_O \quad (6-13)$$

$$P_E = I_F V_F D \text{ (Duty Cycle)} \quad (6-14)$$

$$P_O = P_{O(BIAS)} + P_{O(SWITCHING)} \quad (6-15)$$

$$= I_{CC}(V_{CC} - V_{EE}) + E_{SW}(R_G, Q_G) \cdot f$$

In a DC-DC converter scenario I_F (worst case) = 16 mA, $R_G = 30 \Omega$, D_{MAX} (Max Duty Cycle) = 80%, $Q_G = 500\text{nC}$, $f = 70 \text{ kHz}$ and $T_A \text{ max} = 85^\circ\text{C}$.

$$P_E = 16 \text{ mA} \cdot 1.8 \text{ V} \cdot 0.8 = 23 \text{ mW}$$

$$P_O = 4.25 \text{ mA} \cdot (15 \text{ V} - 0 \text{ V}) + 3 \mu\text{J} \cdot 70 \text{ kHz}$$

$$= 63.75 \text{ mW} + 210 \text{ mW}$$

$$= 273.75 \text{ mW} > 178 \text{ mW (PO(MAX) @ } 85^\circ\text{C)}$$

By considering an excess of $P_{O(MAX)}$, R_g is increased according to the following equation.

$$P_{O(SWITCHING\ MAX)} = P_{O(MAX)} - P_{O(BIAS)} \quad (6-16)$$

$$= 273.75\text{ mW} - 63.75\text{ mW} = 114.25\text{ mW}$$

$$E_{SW(MAX)} = \frac{P_{O(SWITCHING\ MAX)}}{f} \quad (6-17)$$

$$= \frac{114.25\text{ mW}}{70\text{ kHz}} = 1.6321\text{ }\mu\text{J}$$

R_g is chosen as $100\text{ }\Omega$ due to the value of $E_{SW(MAX)}$ to not exceed the maximum conditions. The optocoupler and transistor input circuits are shown in Fig 6.14.

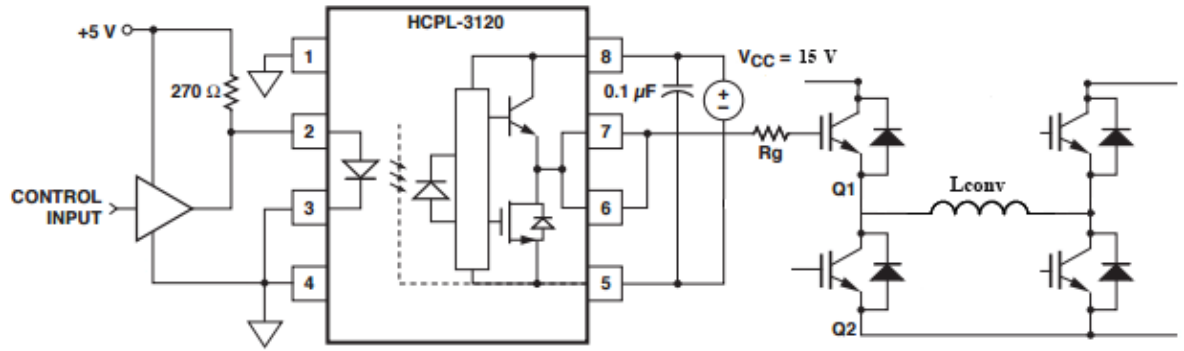


Figure 6-14 HCPL-3120 DC-DC converter application circuit. [59]

Additional R_g analysis is achieved over the converter by applying three different R_g values and observing the ringing results the during switching which is illustrated in Fig 6.15.

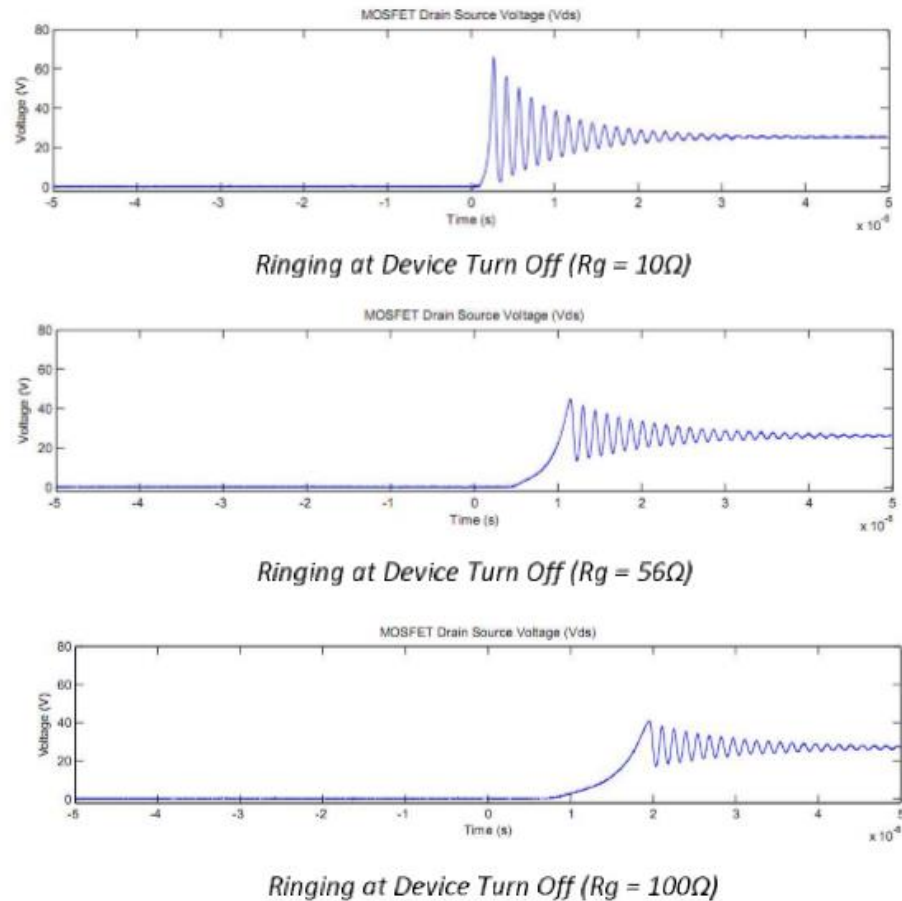


Figure 6-15 Ringing analysis at different R_g values.

6.2.1.4 Small Power DC-DC converters

1 Watt and 2 Watt DC/DC Converters are applied into the system to supply an isolated voltage to the interface circuit between the signal generator and the converter circuit. The implementation of small power converters provides a noise reduction, voltage isolation and ground loop prevention.

In a 1 Watt converter circuit, an input voltage of 12 VDC $\pm 10\%$ is applied and a 15 VDC 65 mA 80% efficiency at the output is obtained. In a 2 Watt converter circuit, the input voltage of 12 VDC $\pm 10\%$ is applied and a 5 VDC 400 mA 77% efficiency at the output is obtained.

6.2.2 Dead Time Circuit

The required logic signals for the MOSFET buck and boost operating modes are logic`1`, logic`0` and D which is a PWM signal with an attended duty cycle. To obtain the three logic signals, two switching signals and a decoder are used to operate the H-Bridge DC-DC converter. A simplified switching operation system is shown in Fig 6.16.

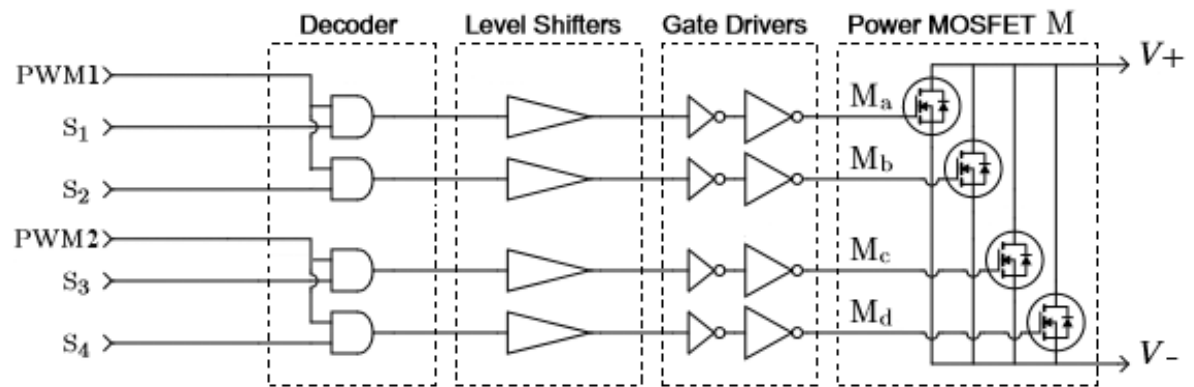


Figure 6-16 MOSFET signal decoding operation schematic. [94]

In addition, as a result of analysing the H-Bridge converter it is observed that the conduction losses are predominant over the switching losses at the PWM controller frequencies which are less than 100 kHz.

6.2.2.1 Shoot-through protection

In full bridge converters the high and low side transistors should not be switched on at the same time. A resistance with a low value occurs between the input and ground if the switches are turned on simultaneously. Due to this low resistance problem, several consequences occur and in the best scenario, the short circuit protection system activates and the system only loses power. If the protection system does not activate, a high amount of current flows across the components

and this can cause heating and a fault in the system. The transistors, PCB traces and power supply components can heat up and break. However, in supply mode blocking diodes are placed to protect the thermoelectric modules from these shoot-through and short circuit conditions. To avoid this situation, the high and low side transistors are not switched on simultaneously.

Due to this operating system, a dead time circuit must be applied into the system to prevent shoot through. When the transistor is switched off, the dead time implements into the switching signal to add a fixed delay before the low side transistor is switched on. Switching without a delay causes a low resistance and therefore a current-spike occurs in the system. To eliminate shoot through, the low side transistor is switched on with a delay by applying a turn off time when the high side transistor is switched off. The same requirement of a delay time is necessary for switching from low to high side as well. This prevention method is determined with several names such as shoot through protection and dead time.

To apply a dead time can cause loss if the delay time exceeds the required time. Especially in high frequency applications, in the region of megahertz, the delay time operation must keep tight to decrease the power loss. In this project, the switching frequency is less than 100 kHz, therefore the period is more than $10\mu\text{s}$ which provides a flexible space for the dead time window.

6.2.2.2 External shoot-through protection circuits

$$V_{STEP} \approx R_T C_{GD} \frac{V_{IN}}{T_R} \left(1 - e^{-\frac{T_R}{R_T(C_{GD}+C_{GS})}} \right) \quad (6-18)$$

where, $R_T = R_{DRIVER} + R_{GATE} + R_{DAMPING}$ and T_R is the rise time.

$$V_{STEP(MAX)} \approx V_{IN} \frac{C_{GD}}{C_{GD}+C_{GS}} \approx 0.37V \quad (6-19)$$

Table 6-1 MOSFET and converter parameters. [60]

R_{Gate}	R_{DRIVER}	$R_{DAMPING}$	V_{IN}	$C_{GD} + C_{GS}$	C_{GD}
1 Ω	5 Ω	100 Ω	48 V	7400 pF	57 pF

According to the datasheet of the transistor, the delay time for a 1MHz application is a turn off time of 80ns and a fall time of 17ns. Due to the adaptations of the current project, and using the above equation, the applied dead time within the additional safety delay is 220ns.

Table 6-2 MOSFET delay time parameters. [60]

Input capacitance	C_{iss}	$V_{GS}=0$ V, $V_{DS}=50$ V, $f=1$ MHz	5600	7400	pF
Output capacitance	C_{oss}		710	940	
Reverse transfer capacitance	C_{rss}		38	57	
Turn-on delay time	$t_{d(on)}$		19	28	

Rise time	t_r	$V_{DD}=50\text{ V},$	24	36	ns
Turn-off delay time	$t_{d(off)}$	$V_{GS}=10\text{ V},$	53	80	
Fall time	t_f	$I_D=25\text{ A},$ $R_G=2.7\ \Omega$	12	17	

To perform a delay time R/C circuits are used to provide the required shoot through protection. The dead time circuit is illustrated by:

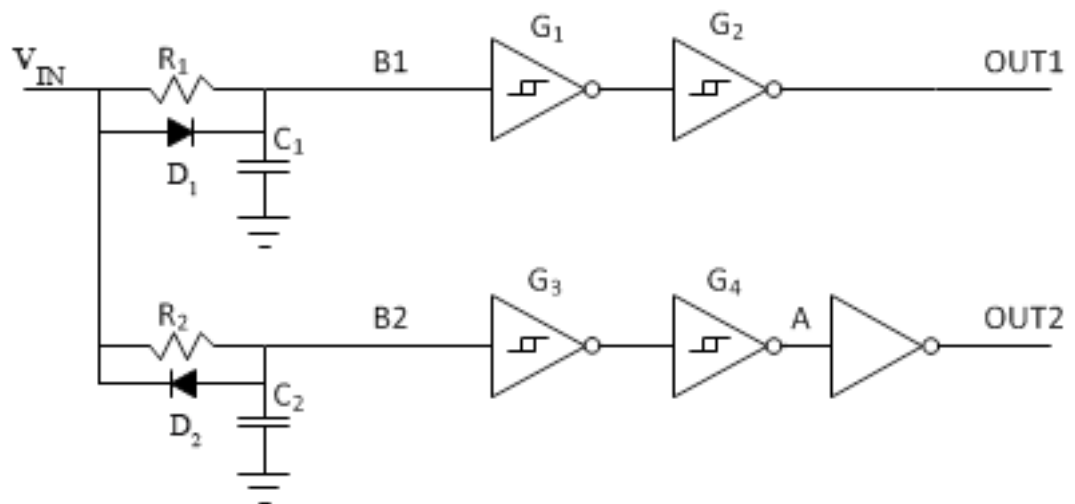


Figure 6-17 Dead time circuit for gate driven signal. [95]

The Schmitt trigger provides feedback to the input signal, which amplifies the voltage value and a fast switch from the low level to high level as well as the other way around. A basic Schmitt trigger operation method is illustrated in Fig 6.18.

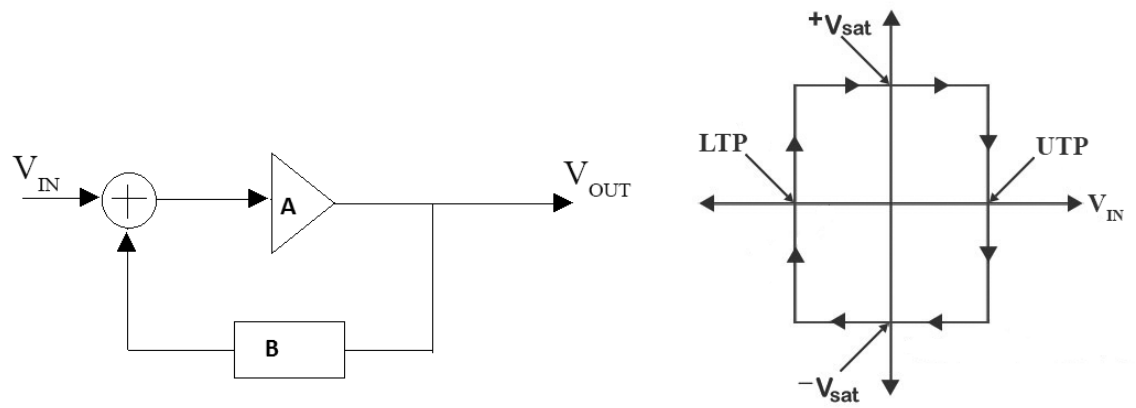


Figure 6-18 Schmitt trigger equivalent circuit and operation method.

The signal processing through the dead time circuit is illustrated by:

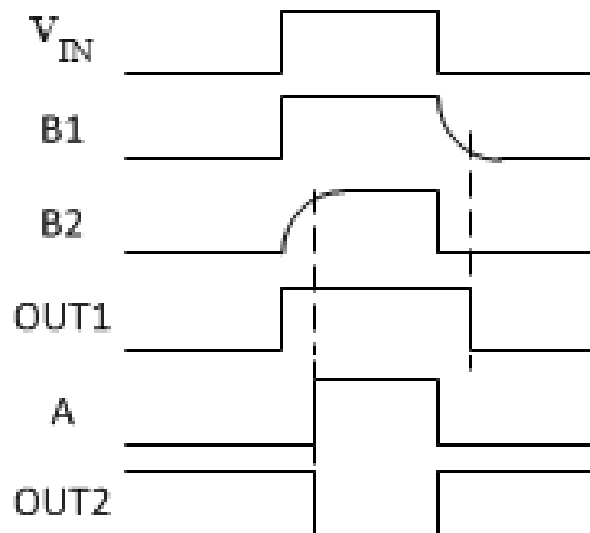


Figure 6-19 Modified signals through dead time circuit. [95]

As illustrated in Fig 6.17, an R/C circuit modifies the input signal with an RC curve. The modified signal acts as a Schmitt trigger input signal which adds dead time into the signal due to its falling edge threshold voltage. A similar method applies to the rising edge as well; the added RC curve causes a delay at the second output rising edge and therefore the shoot through protection system prevents both MOSFETs from being switched on at the same time. The Schmitt

trigger circuit also provides a noise reduction, for that reason the signal is passed through a double Schmitt trigger to obtain a more accurate signal. As shown in Fig 6.17 and Fig 6.19, the falling edge of the first output is illustrated by:

$$t_{out1} = -R_1 C_1 \ln \left(\frac{V_{tl}}{V_{oh}} \right) \quad (6-20)$$

where, V_{tl} is the Schmitt-trigger low level voltage and V_{oh} is the input gate's high level voltage output. The rising edge of the second output is shown by:

$$t_{out2} = -R_2 C_2 \ln \left(1 - \frac{V_{th}}{V_{oh}} \right) \quad (6-21)$$

where, V_{th} is the Schmitt-trigger high level voltage. Due to the operating system of the Schmitt-trigger, the low level threshold voltage is $V_{oh}/3$ and the high level threshold voltage is $2 * V_{oh}/3$. Therefore, the time delays are approximately equal to $R_1 C_1$ and $R_2 C_2$. t_{out1} are applied higher than t_{out2} due to the high off time delay even though 220ns is enough to the prevent shoot through condition. Calculation of t_{out1} and t_{out2} is shown by:

$$t_{out1} = -250\Omega \cdot 1nF \cdot \ln \left(\frac{1}{3} \right) = 250ns \quad (6-22)$$

$$t_{out2} = -220\Omega \cdot 1nF \cdot \ln \left(1 - \frac{2}{3} \right) = 220ns \quad (6-23)$$

6.3 H-Bridge DC-DC Converter Experiment

6.3.1 H-Bridge Buck Mode Experiment

The buck conversion testing of the H-bridge converter is completed by using the configuration in Fig 6.20. During the Buck conversion, the Boost segment HSTs

are set to closed mode and the LSTs are set to open mode. The H-Bridge converter is illustrated in Fig 6.20 and Fig 6.24 during the Buck and Boost mode operation, respectively.

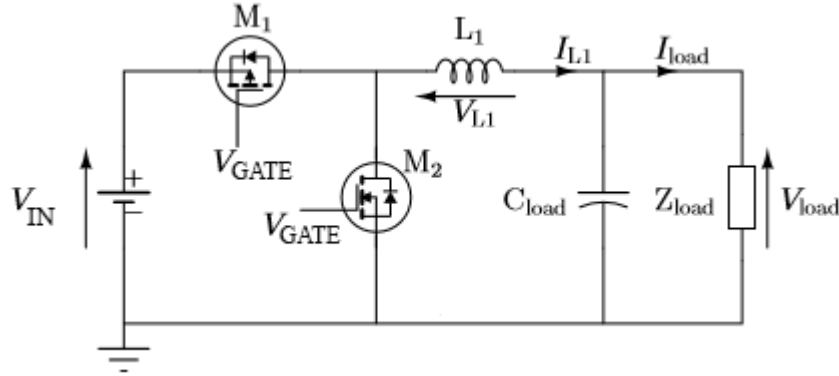


Figure 6-20 H-Bridge Buck mode testing.

To test the circuit in the buck mode, an input voltage of 20V was supplied to the converter with a signal generator supplying a 5V square wave with a duty cycle equal to 0.5. Fig 6.21 displays the input voltage, output voltage and inductor current. It can be shown with the use of Eq. (6-24) repeated below that the output voltage of the buck converter matches that of the theory.

$$\frac{V_{OUT}}{V_{IN}} = \frac{t_{ON}}{T_s} = \frac{D_1}{1-D_2} = D_1 \text{ where } D_2 = 0 \quad (6-24)$$

$$V_{OUT} = V_{IN} \times D_1 = 20 \times 0.5 = 10V$$

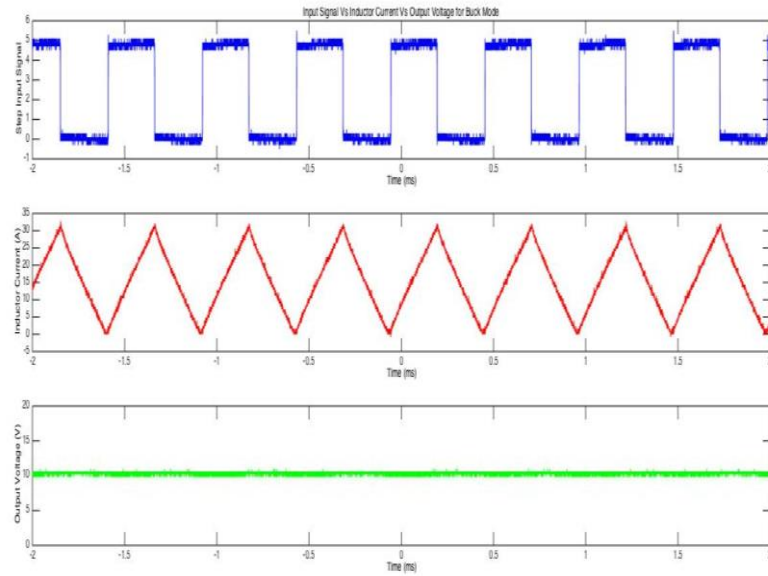


Figure 6-21 H-Bridge Buck mode $D=0.5$ testing.

The H-Bridge converter buck mode is tested at quarter and three quarter duty cycle mode to analyse the CCM and DCM operations. The measurements are illustrated in Fig 6.22 and Fig 6.23, respectively.

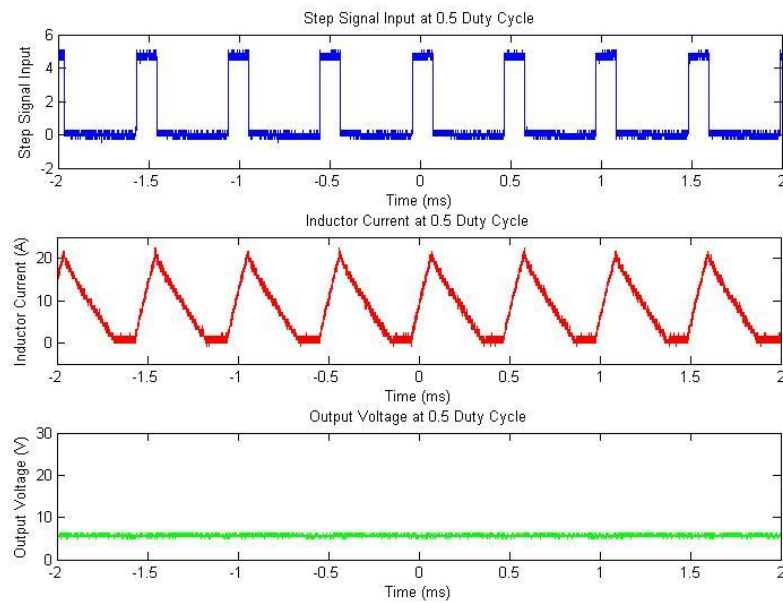


Figure 6-22 H-Bridge Buck mode $D=0.25$ testing.

$$V_{OUT} = V_{IN}D_1 = 20 \times 0.25 = 5V \quad (6-25)$$

When the duty cycle of the converter is set to a quarter duty cycle in Buck mode, the H-Bridge goes into the DCM operation because of the inductor current which decreases to zero during one part of the period. The reason for this discontinuous mode is the low duty cycle level which prevents the storage of enough energy in the inductor for it to operate for the rest of the period. Falling to zero causes a discharge at the output capacitor hence an increase in switching losses. This fall can be prevented with a pulse frequency modulation PFM. In Eq. (6-26), the stored energy in the inductor is illustrated.

$$E_L = \frac{1}{2}LI^2 \quad (6-26)$$

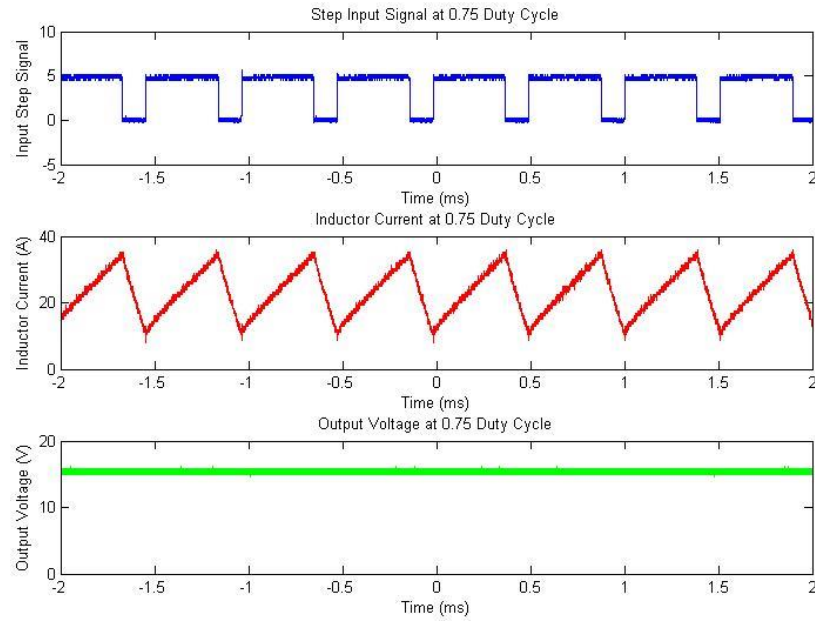


Figure 6-23 H-Bridge Buck mode D=0.75 testing.

$$V_{OUT} = V_{IN}D_1 = 20 \times 0.75 = 15V \quad (6-27)$$

6.3.2 H-Bridge Boost Mode Experiment

In the boost mode of the H-Bridge converter which is shown in Fig. 6.24, the high side transistors HSTs become closed, therefore the output capacitor is charged during 'on' duty cycle, D . This stored energy is used to supply power to the load during the 'off' duty cycle $(1-D)$ where the HSTs switch to the open mode. During the 'off' duty cycle of the HSTs, the low side transistors LSTs become closed and the energy is stored in the inductor, which is used to supply additional power to the load when the HSTs switch to the closed condition. Therefore, the output voltage steps up, which is also called the Boost mode.

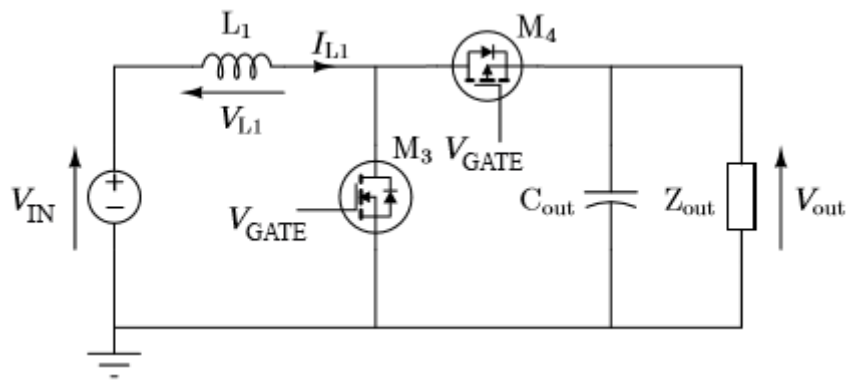


Figure 6-24 H-Bridge Boost mode testing.

The H-Bridge converter boost segment is tested with a 10V input voltage. As calculated according Eq. (6-28) and compared with the Fig. 6.25 which plots output signals, the estimated and observed output values are almost the same with the slight difference being due to the power losses in the converter in practice.

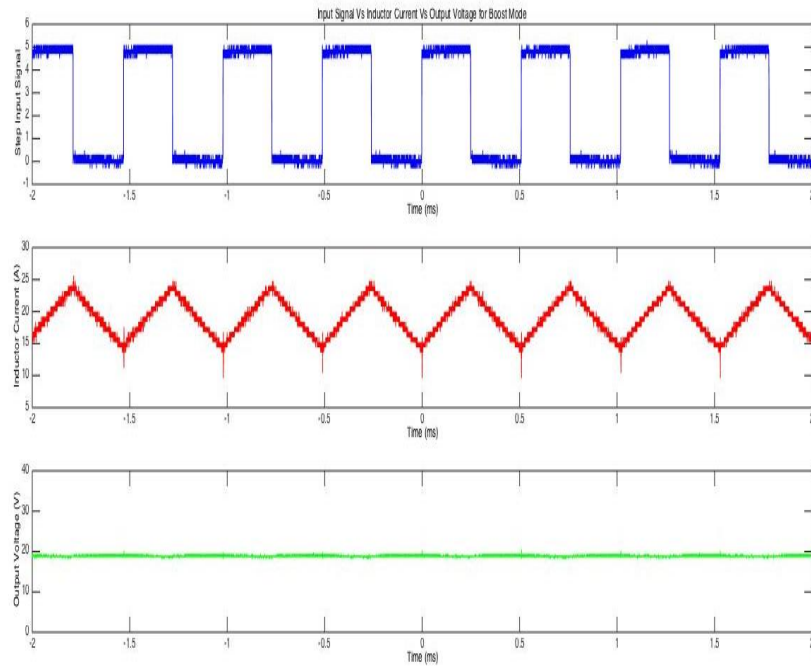


Figure 6-25 H-Bridge Boost mode D=0.5 testing.

$$\frac{V_{OUT}}{V_{IN}} = \frac{T_s}{t_{OFF}} = \frac{D_1}{(1-D_2)} = 10 \frac{1}{(1-0.5)} = 20V \quad \text{where } D_1 = 1 \quad (6-28)$$

The H-Bridge converter boost mode is also tested with a quarter duty cycle and the results are illustrated in Fig 6.26. In contrary to the Buck mode, the inductor current does not fall to zero due to the direct connection of the source in the Boost conversion.

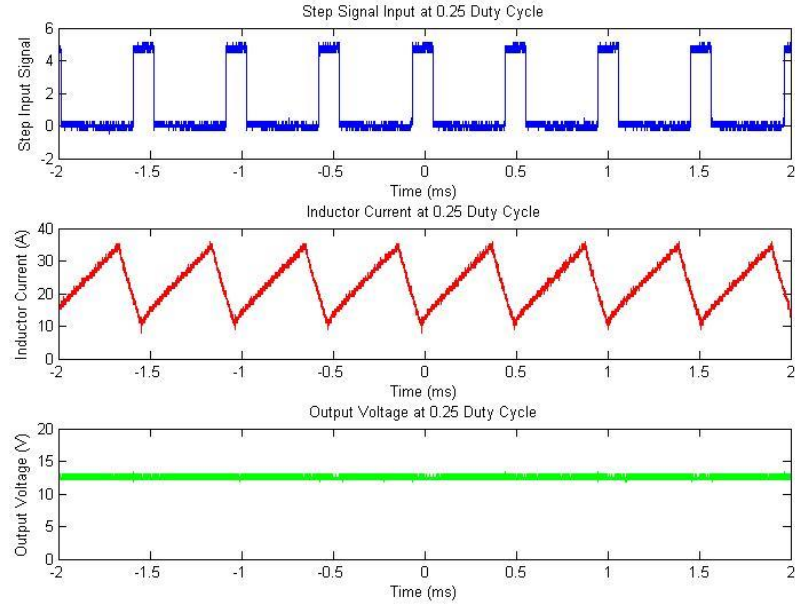


Figure 6-26 H-Bridge Boost mode D=0.25 testing.

$$V_{out} = V_{in} \frac{1}{(1-D_2)} = 10 \frac{1}{(1-0.25)} = 13.3V \quad (6-29)$$

6.3.3 48V Output Voltage Testing

To obtain a 48V voltage output in the H-Bridge converter a 24V power supply is applied into system. According to the conversion ratio, a half duty cycle is implemented into the system to double the input voltage, which is illustrated by:

$$M = \frac{V_{OUT}}{V_{IN}} = \frac{D_1}{1-D_2}$$

$$2 = \frac{1}{1-D_2}$$

$$D_2 = 0.5$$

A power supply with a high current is applied into the system for measurement therefore an additional protection circuit is also applied between the source and

the converter. In addition to the 48V conversion, different load values are also applied as the load to understand and analyse possible match load operations which vary up to $10\ \Omega$, corresponding to a large scale TEG generator simulation program. $R_1 = 10\ \Omega$, $R_2 = 5\ \Omega$ and $R_3 = 3.3\ \Omega$ was implemented as shown in the following figures:

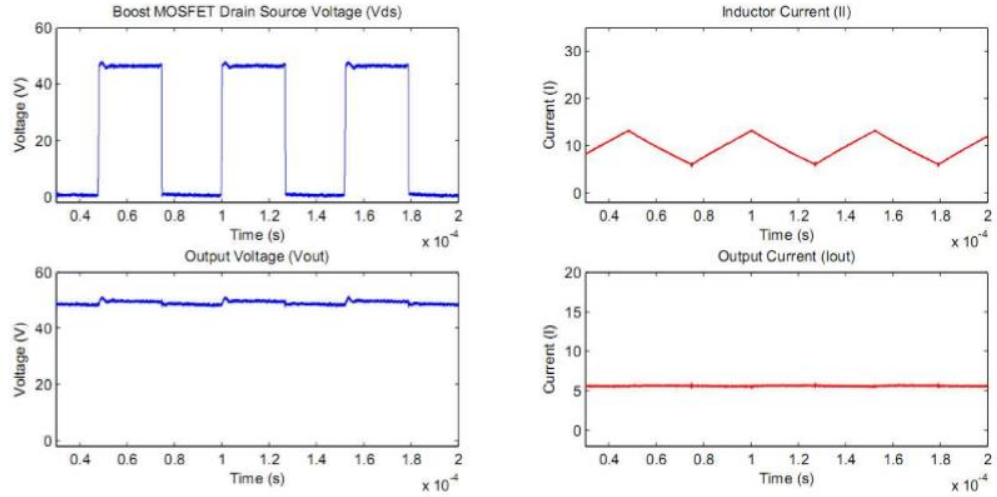


Figure 6-27 Converter signals when $10\ \Omega$ load resistor is applied to system.

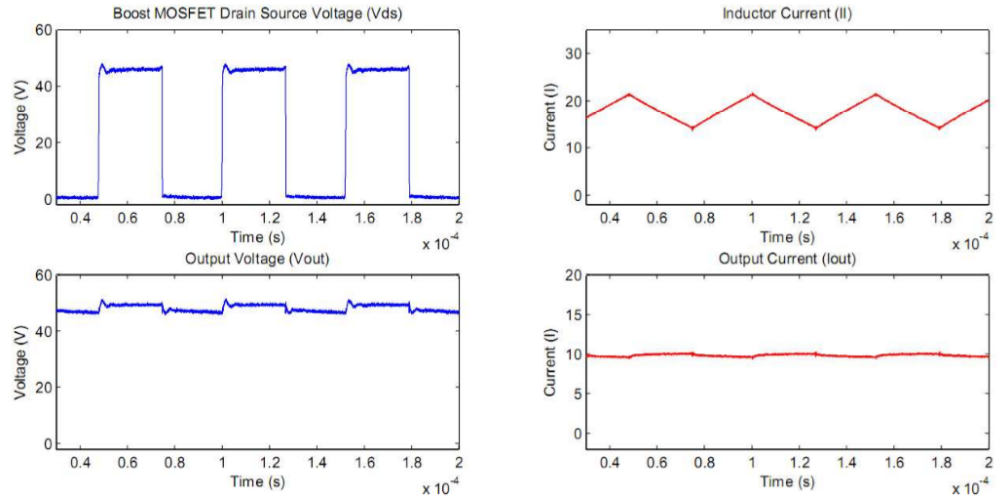


Figure 6-28 Converter signals when $5\ \Omega$ load resistor is applied to system.

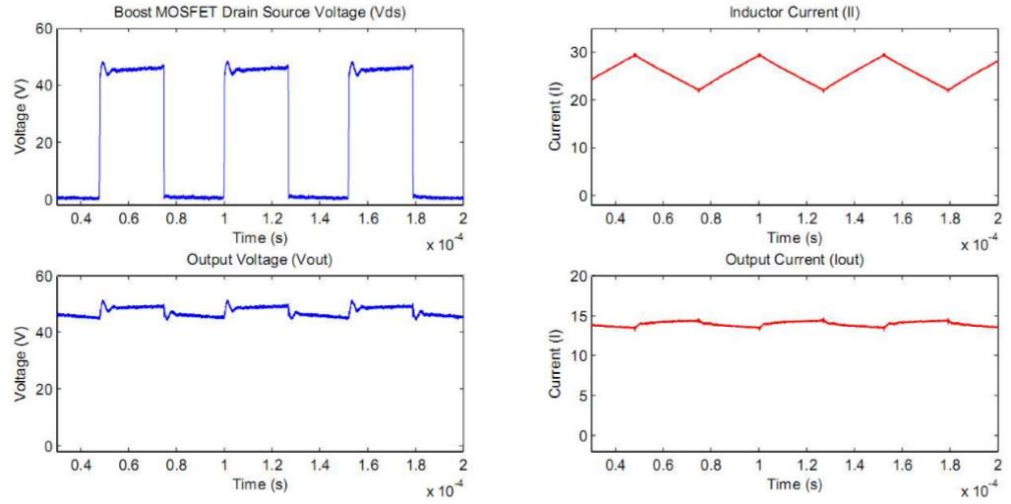


Figure 6-29 Converter signals when 3.3Ω load resistor is applied to system.

6.4 Maximum Power Point Tracking Algorithms

At a constant temperature, the generated power varies according to the output load. When the TEG terminals are not connected to the load or short circuited, the generator does not provide useful electrical energy, contrary to any alternative point in the I-V line of thermoelectric power generator. The MPP is obtained in the middle of the I-V line where the TEG electrical potential is the half of the open-circuit electrical potential or half of the short circuit current is the system current. In the statement of the ideal conditions and when the temperature difference between both sides is constant, load resistance is illustrated by:

$$R_{LOAD} = \frac{\frac{V_{OC}}{2}}{\frac{I_{SC}}{2}} \quad (6-30)$$

It is unrealistic to keep the temperature gradient constant and also to have only the resistive load at the output, for that reason it is impossible to get a maximum power by placing only the resistance at the load. In addition, the output voltage alters in time according to the power usage by the load, this is the second reason that only considering the resistor placement is not enough to obtain maximum power.

The waste heat recovery implementations use the thermal energy which is wasted if not recovered, consequently the thermoelectric power generation thermal energy to electrical energy conversion performance is not an important disadvantage, however optimising the generator power output is significant to decrease the cost per Watt. If the generated electrical energy is surplus to requirements to run system according to the load requirement, the extra power is used to charge batteries.

The applied temperature gradient between the thermoelectric generator's sides alters almost all the time. Independent of the thermal status the I-V line output point often requires regulation due to tracking of the maximum power point. In this manner, DC-DC converters are placed for the MPPT to obtain maximum power production. These DC-DC converters are operated by the maximum power point tracking algorithm to reach the best I-V line point, the duty cycle alteration provides this tracking operation. The load resistance becomes equal or higher than the internal resistance when the generator reaches the ideal operating point.

The maximum power point tracker generally connects the generator to the storage components, for instance the supercapacitor or battery. The second converter can be placed to transmit power with a fixed voltage from the supercapacitor or the battery when the load demands a constant voltage for an appropriate process.

The perturb and observe and incremental conduction MPPT methods are generally applied to systems for variable voltage generators. Due to the fact that the form of the power voltage curve of photovoltaic systems is logarithmic, these methods are called hill-climbing systems and primarily they are designed for photovoltaic applications. Another method which is used in some TEG applications in literature is extremum seeking control (ESC) which applies to a system with less information due to its non-model dynamic regulation method.

The fractional open circuit model demands a voltage measurement alone and a less complex algorithm contrary to P&O, INC, ESC and other methods, which need a voltage and current measurement and a more complex algorithm.

6.4.1 Perturb & Observe MPPT Method

The main process topology of the P&O method frequently requires to perturb an electrical managing point and observing the results of the system. Within these algorithms, the management point alters through the power current curve and the output power reaches a maximum point by comparing the power measurements. The perturb and observe method's algorithm is illustrated in Fig 6.30.

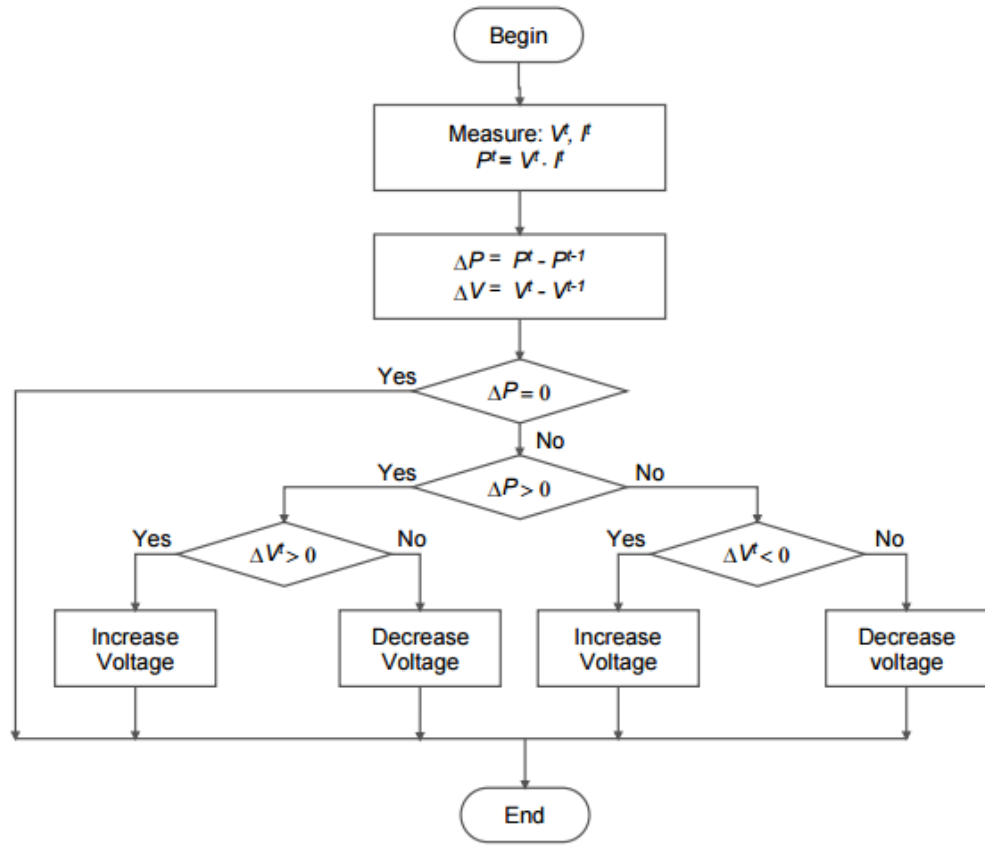


Figure 6-30 MPPT algorithm of conventional perturb and observe method. [96]

In the traditional perturb and observe method, the source voltage and current are measured to find a power value and a constant V_{STEP} is applied to reach a maximum power point. The variance of thermoelectric generator power ΔP is illustrated by:

$$\Delta P = P_{TEG}^{t+1} - P_{TEG}^t \quad (6-31)$$

The operation flow of a maximum power point tracking system, where ξ is the tolerance of ΔP , is shown by:

- $|\Delta P| < \xi$ represents that the change of ΔP is negligible and the system has reached MPP. Because of that, further adjustment is not required and the next iteration initiates.
- If ΔP is bigger than the tolerance, the algorithm determines that the operating point falls on which side of the MPP by the sign of ΔP .
- $\Delta P > 0$ represents that the operating point is on the left side of the maximum power point.
- If $|\Delta P| > \xi$, $\Delta P > 0$ and the next voltage value is bigger than the present voltage value, the current voltage is on the left side of the MPP, therefore to obtain the MPPT the next voltage will be set on a higher voltage amount.
- If $|\Delta P| > \xi$, $\Delta P > 0$ and the next voltage value is lower than the present voltage value, the current voltage is on the right side of the MPP, therefore to obtain the MPPT the next voltage will be set on a lower voltage amount.
- $\Delta P < 0$ represents that the operating point is on the right side of the maximum power point.
- If $|\Delta P| > \xi$, $\Delta P < 0$ and the next voltage value is higher than the present voltage value, the current voltage is on the right side of the MPP, therefore to obtain the MPPT, the next voltage will be set on a lower voltage amount.
- If $|\Delta P| > \xi$, $\Delta P < 0$ and the next voltage value is lower than the present voltage value, the current voltage is on the left side of the MPP, therefore to obtain the MPPT, the next voltage will be set on a higher voltage amount.

There are two main disadvantages of the conventional perturb and observe methodology. The first disadvantage is the response time for an instantaneous change on the source side to reach the MPP. However, in high volume TEG

applications, the P&O response time becomes acceptable, due to the thermal response for an instantaneous change at exhaust gas temperature. In addition to the thermal response, the adjustment of the perturbation step size V_{STEP} provides more efficiency and the enhancement of the P&O response time, therefore it provides an adaptation between the transient and steady state conditions of the system. This MPPT methodology is called adaptive perturb and observe (APO) method. In conventional P&O methods, the perturbation step is constant: If it is chosen as a low value, the response time becomes insufficient to reach the MPP and if it is chosen as a high value, it causes an increase in the current ripple and oscillations around the MPP in the steady state condition. Under the consideration of two step sizes, the adaptive system is applied into the P&O MPPT by adjusting the step size to a low value at the steady state condition and a high value at the transient condition. To obtain this adaptation, the step size is adjusted as follows:

$$\eta = \frac{\Delta P}{\Delta P_{MAX}} \quad (6-32)$$

$$V_{REF} = V_{REF} \pm \eta V_{STEP} \quad (6-33)$$

η is a coefficient that determines the adjustable step size, ΔP_{MAX} indicates the maximum value of ΔP and the reference voltage for the following loop is represented by V_{REF} . The algorithm is adapted to react more when the power variance is high and react less by decreasing the perturbation step when the power variance is low.

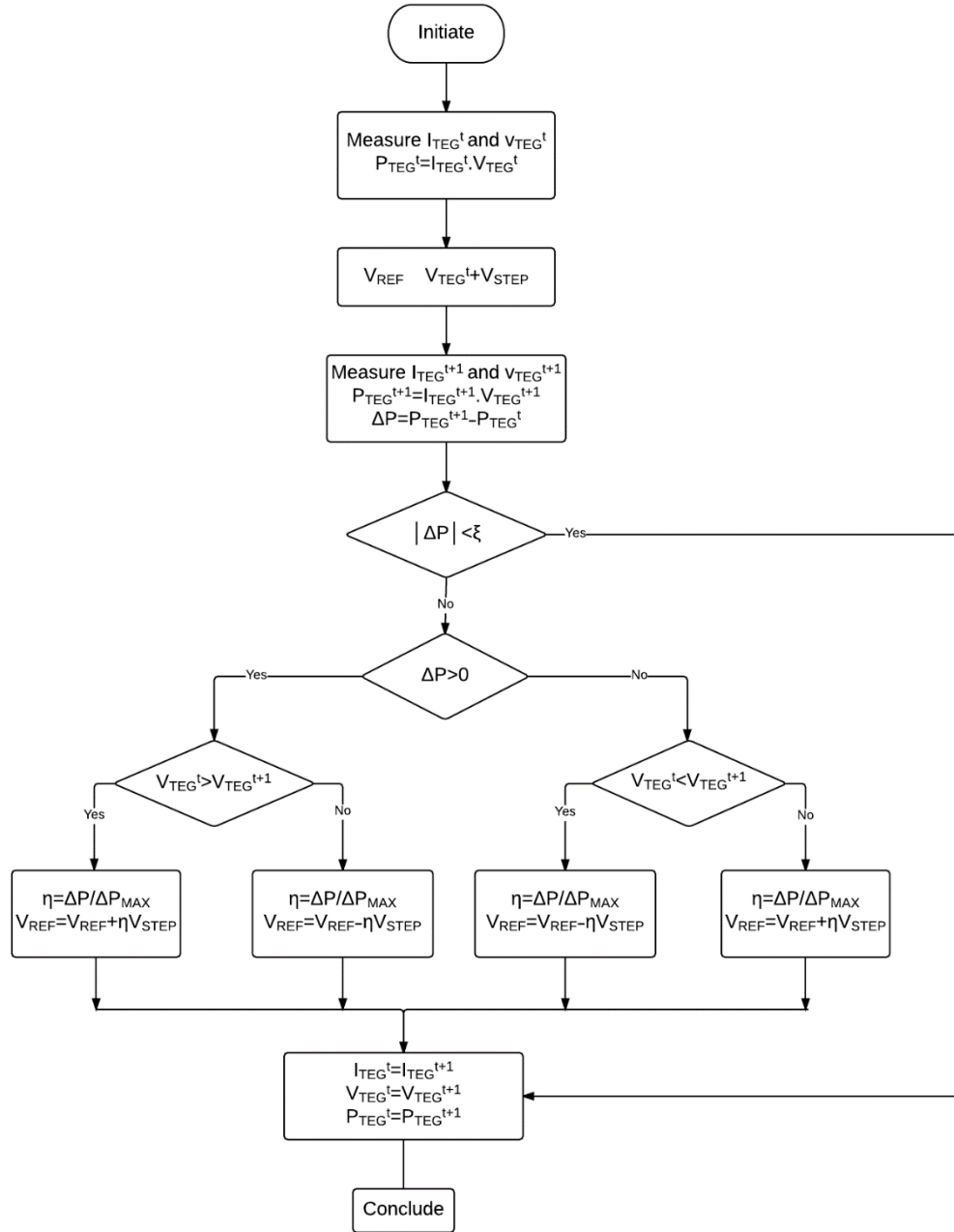


Figure 6-31 Adaptive perturb and observe algorithm. [97]

The initial perturb and observe algorithm faces two primary disadvantages when it applies a constant frequency and perturbation step into the system. One of the disadvantages, which is also called limit cycle oscillation, occurs at a stabilised temperature difference, the algorithm's MPP fluctuates on both sides of the actual MPP because of the unceasing perturbation. The second disadvantage is

the difficulty of the reaching maximum power point under a fast temperature gradient alteration. An adaptive perturb and observe method modifies the perturbation step and the frequency to decrease the fluctuation around the actual MPP at temperature gradient equilibrium also it provides a rapid approach to the MPP and an accurate real time response. A disadvantage of the adaptive P&O method which is shown in Fig. 6.31, is increase of the number of measurements and computations due to a decrease of the perturbation value and an increase of P&O frequency.

6.4.2 Offline Incremental Conductance MPPT

The incremental conductance method which is also called INC or IC, operates due to the inclination of the power current curve, the gradient of the power corresponding to the gradient of the current is equal to zero when it reaches the maximum power point. In addition, if the output power is on the left side of the MPP, $\frac{dP}{dI}$ is higher than zero and if the output power is on the right side of the MPP, $\frac{dP}{dI}$ is lower than zero.

$$\frac{dP}{dI} = \frac{dVI}{dI} = I \frac{dV}{dI} + V \cong I \frac{\Delta V}{\Delta I} + V \quad (6-34)$$

The maximum power point can be reached by comparing the incremental conductance $\frac{\Delta I}{\Delta V}$ and immediate conductance $\frac{I}{V}$ as illustrated in Fig 6.32.

The adaptive methodology which is applied to the perturb and observe algorithm can be applied into the IC method by altering the step size to enhance the speed and precision of the MPP approach.

6.4.2.1 Offline MPPT technique

The measurement of the generator's V_{oc} can be achieved by turning off the first transistor of the H-Bridge converter and gauging the generator's voltage. The open circuit voltage measurement of the MPPT topology is demonstrated in the next section particularly and a technical investigation of the voltage measurement unit's power loss because of the applied elements and measurements.

6.4.2.2 Open-circuit voltage MPPT method

The measurement of the generator's V_{oc} and subsequent adjustment the output voltage to half of the open circuit voltage is called FOCV, fractional open circuit voltage. This principle generally demands a disconnection between the converter and the source during the charging of the input capacitor which reaches the open circuit voltage value, this disconnection causes a disruption of the energy transfer between the generator and the load. Corresponding to the internal resistance, the input capacitor value should be tens of micro Farads which demands hundreds of micro seconds to reach the open circuit voltage, due to having to fulfil the input current requirements. In some of the converters, a supplementary transistor in series is required to cut the connection between the generator and the load and the supplementary transistor demands a high side switch during this disconnection. The disconnection transistor causes a supplementary I^2R loss when in the switched off operation and interferes with the converter's ordinary process.

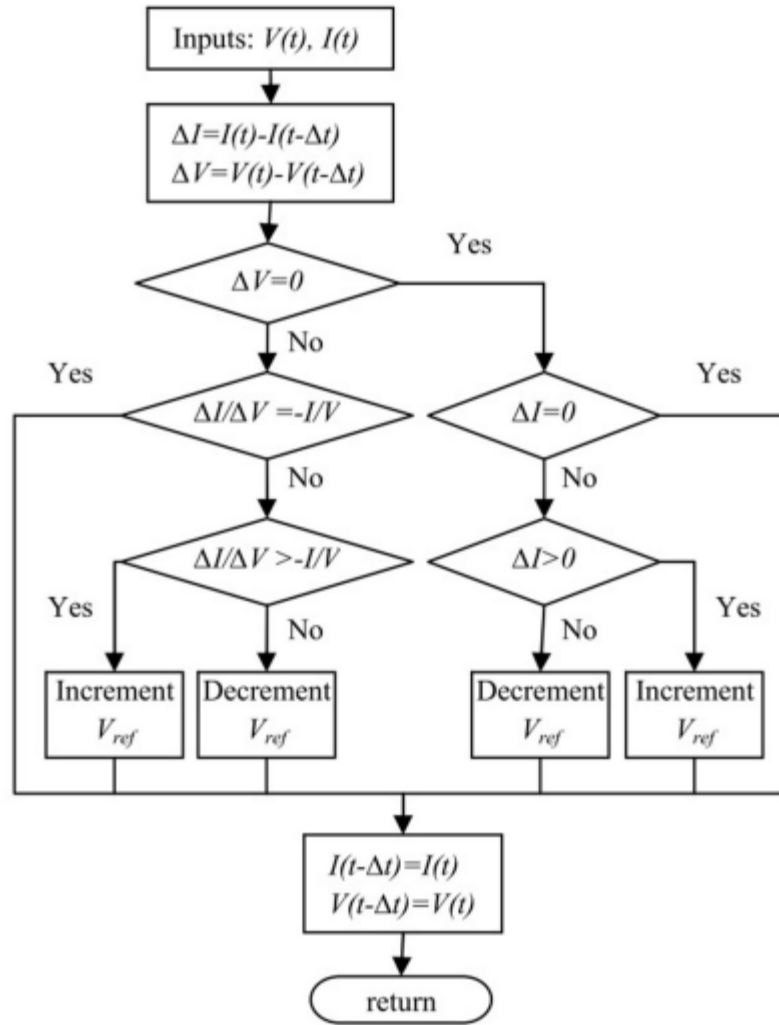


Figure 6-32 MPPT algorithm of incremental conductance method. [98]

The open circuit voltage measurement of the generator can be deployed with the input transistor which is originally found in Buck-Boost converters. When the input transistor cuts the connection between the TEG and the converter, the open circuit voltage measurement unit, which is connected to the generator in parallel, realises the monitoring voltage value as illustrated in Fig 6.33. the Buck-Boost converter input is linked to the thermoelectric generator and the input capacitor of the converter is connected to the thermoelectric generator in parallel via a transistor, while the first transistor of the H-Bridge converter acts as an input switch for disconnection.

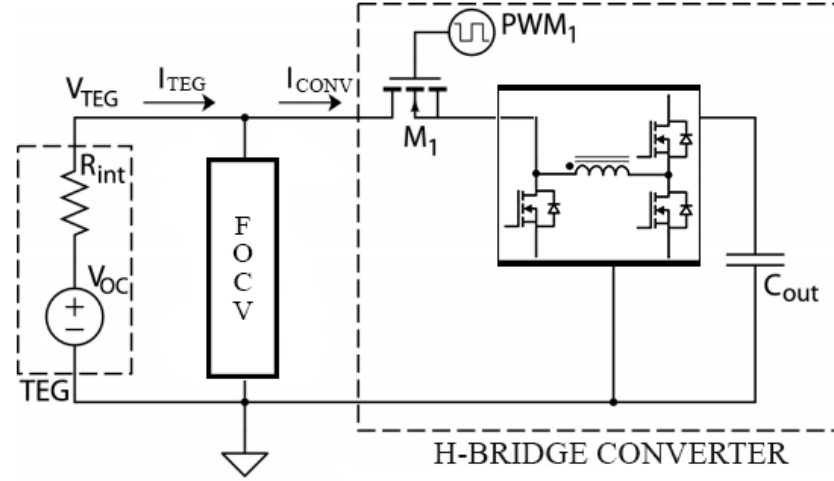


Figure 6-33 Open circuit voltage measurement unit.

During the normal process of a converter, the Voc transistor is held in the ‘on’ position and the Voc capacitor provides the input filtration. During the open circuit voltage measurement, the Voc transistor is held in the ‘off’ position while the first switch of the H-Bridge converter can cut the connection between the converter and the generator at open conditions. The Voc capacitor cannot be fed by the input current during the measurement, therefore the generator reaches the open circuit voltage in nanoseconds. The DC-DC converter controller unit continues to produce PWM signals during the measurement, which does not actually provide conversion. Due to the generator’s thermal time constant, which is observed from experimental data and the given characteristics of the TE unit, the sampling time of Voc is set to 500 milliseconds under the consideration of the thermal time constant, as illustrated in Eq. (6-34), and the actual sampling unit requirements. The controller unit alters the duty cycle of the converter to obtain the half value of the open circuit voltage amongst the measurements.

$$\tau = \frac{\rho C_P V}{h A_S} \quad (6-35)$$

During the measurement, the Peltier effect becomes negligible due to the open circuit mode, hence the temperature gradient rises, and then the open circuit voltage. In addition, the reference voltage is increased due to the rise in the temperature gradient. The thermoelectric generator is held in the open circuit mode for less than a period when the controller operates at 78 kHz and until the measurement is concluded, the thermal management point remains stable. Variation of the load side, which affects the H-Bridge output, does not have any influence on the open circuit voltage amount, therefore an MPP approach can be achieved.

6.4.2.3 Analysis of MPPT efficiency

The power loss determination of the open circuit voltage measurement unit is examined in this section due to supplementary transistor and capacitor components as well as the disconnection between the TEG and the converter. The root mean square value calculation of the open circuit voltage capacitor's current and the H-Bridge's reaction analysis to the measurement method is required to obtain a power loss computation.

During the 'off' condition of the H-Bridge, the first transistor open circuit voltage capacitor is charged by the thermoelectric generator and the stored energy is transferred to the output of the converter during the 'on' condition of the first transistor. The input current of the TE generator value is restricted by the internal resistor, which varies from a quarter to a few ohms. At the

thermoelectric modules, the input current of the converter fluctuates due to the Voc capacitor.

The converter's input current is transferred to the H-Bridge when the first transistor is in the closed condition and when it is in the open condition, the generators current charges the Voc capacitor when the Voc transistor is in the 'on' mode. The applied Voc capacitor also provides a filtration at the input. The TEG current is calculated by adding the Voc capacitor current to the converter current. When the H-Bridge reaches the maximum power point, the Voc capacitor's average voltage value becomes half of the open circuit voltage of the TEG. The Voc capacitor current is illustrated when it is being charged by the TEG by:

$$I_{Voc}(t) = \frac{V_{oc}}{2R_{TOTAL}} e^{-\frac{t}{\tau}} \quad (6-36)$$

where τ is $R_{TOTAL} \cdot C_{Voc}$ and R_{TOTAL} is the total value of the TEG internal resistor and the ESR value of the Voc capacitor. The root mean square value of the Voc capacitor current is illustrated by:

$$\begin{aligned} I_{Voc_{RMS}}^2 &= \frac{1}{T_{SW}} \int_0^{t_{open}} \left(\frac{V_{oc}}{2R_{TOTAL}} \right)^2 e^{-\frac{2t}{\tau}} dt \quad (6-37) \\ &= \frac{1}{T_{SW}} \frac{V_{oc}^2}{4R_{TOTAL}^2} \frac{\tau}{2} \left(1 - e^{-\frac{2t_{OFF}}{\tau}} \right) \\ &= \frac{V_{oc}^2 C_{Voc}}{8T_{SW} R_{TOTAL}} \left(1 - e^{-\frac{2t_{OFF}}{\tau}} \right) \end{aligned}$$

When considering the Voc capacitor's voltage ripple, which is negligible, the current calculations during the open condition of the first transistor is illustrated by:

$$I_{VOC} = \frac{V_{OC}}{2R_{TOTAL}} \quad (6-38)$$

$$I_{VOC_{RMS}}^2 = (1 - D)I_{TEG}^2 = (1 - D)\frac{V_{OC}^2}{4R_{TOTAL}^2} \quad (6-39)$$

During the open condition I_{VOC} is equal to I_{TEG} .

When the first transistor is in the closed condition, the RMS value of the Voc capacitor current is illustrated by:

$$I_{VOC_{RMS}}^2 = \frac{D}{3} \left[(I_{TEG} - I_{L_{MIN}})^2 + (I_{TEG} - I_{L_{MAX}})^2 + (I_{TEG} - I_{L_{MIN}})(I_{TEG} - I_{L_{MAX}}) \right] \quad (6-40)$$

In Buck-Boost operations, the inductor current illustrated by:

$$I_{TEG} - I_L = I_{TEG} \frac{1}{M} = I_{TEG} \frac{D-1}{D} \quad (6-41)$$

where, M is the conversion ratio. $I_{L_{MIN}}$ and $I_{L_{MAX}}$ are illustrated by:

$$I_{L_{MIN}} = I_L - \frac{\Delta I_L}{2} \quad (6-42)$$

$$I_{L_{MAX}} = I_L + \frac{\Delta I_L}{2} \quad (6-43)$$

Due to the minimum and maximum inductor current equations, the RMS value of the Voc capacitor current is shown by:

$$I_{VOC_{RMS}}^2 = \frac{D}{3} \left[\left(I_{TEG} \frac{D-1}{D} + \frac{\Delta I_L}{2} \right)^2 + \left(I_{TEG} \frac{D-1}{D} - \frac{\Delta I_L}{2} \right)^2 + \left(I_{TEG} \frac{D-1}{D} + \frac{\Delta I_L}{2} \right) \left(I_{TEG} \frac{D-1}{D} - \frac{\Delta I_L}{2} \right) \right]$$

$$= \frac{D}{3} \left[\left(I_{TEG} \frac{D-1}{D} + \frac{\Delta I_L}{2} \right)^2 + \left(I_{TEG} \frac{D-1}{D} - \frac{\Delta I_L}{2} \right)^2 + \left(I_{TEG} \frac{D-1}{D} \right)^2 - \left(\frac{\Delta I_L}{2} \right)^2 \right] \quad (6-44)$$

In the Buck-Boost methodology, the inductor current ripple is illustrated by:

$$\Delta I_L = \frac{V_{OUT} \cdot (1-D)}{f_{SW} \cdot L} \quad (6-45)$$

When this inductor current ripple is applied into the $I_{V_{OC_{RMS}}}^2$ formula, the equation is illustrated by:

$$I_{V_{OC_{RMS}}}^2 = (1-D)^2 \left(\frac{I_{TEG}^2}{D} + \frac{DV_{OUT}^2}{12f_{SW}^2 L^2} \right) \quad (6-46)$$

The total RMS value of the Voc capacitor current during a full period is illustrated by:

$$\begin{aligned} I_{V_{OC_{RMS}}}^2 &= (1-D)^2 \left(\frac{I_{TEG}^2}{D} + \frac{DV_{OUT}^2}{12f_{SW}^2 L^2} \right) + (1-D)I_{TEG}^2 \\ &= (1-D) \left(\frac{I_{TEG}^2}{D} + (1-D) \frac{DV_{OUT}^2}{12f_{SW}^2 L^2} \right) \end{aligned} \quad (6-47)$$

The Voc MOSFET power dissipation is illustrated by:

$$P_{M_{VOC}} = I_{V_{OC_{RMS}}}^2 r_{ON} \quad (6-48)$$

where, r_{ON} is the MOSFET resistance during the closed condition. The measurement of the Voc operation takes micro seconds to conclude when the measurement period takes 0.1 seconds, therefore the transistor losses, which are both the diode and switching losses during the open condition, can be neglected.

The thermoelectric generator provides power to the H-Bridge when the first transistor is in the closed condition and the generator becomes an open circuit

when the first transistor and the Voc transistor are in the open condition. The internal resistance of the TEG restricts the amount of generator current when the first transistor is in the closed condition and the Voc transistor is in the open condition and also the Voc transistor diode becomes connected, therefore this capacitor provides a supplementary current into the H-Bridge while it is discharging.

The Voc capacitor voltage reduces at every converting cycle due to the disconnection between the Voc capacitor and the ground when the Voc transistor is in the open condition. To accomplish the measurement, the Voc transistor is held in the ‘off’ mode for approximately switching eight periods, and the Voc capacitor is adequate to prevent a high reduction of the input voltage. When the system is in the open circuit voltage measurement mode, the Voc capacitor voltage decrement analysis is investigated as shown below and the capacitor energy during the initial Voc measurement is illustrated by:

$$E_{C_{Voc_0}} = \frac{1}{2} C_{Voc} V_{C_{Voc_0}}^2 \quad (6-49)$$

When the first transistor is in the closed condition and under consideration of $I_{L_{MIN}} - I_{TEG} \geq 0$, the Voc capacitor energy, which flows to the converter is illustrated by:

$$\begin{aligned} E_{C_{Voc_CONV}} &= \int_0^{t_{ON}} V_{C_{Voc}}(t) I_{C_{Voc}}(t) dt \\ &= \int_0^{t_{ON}} \left(I_{L_{MIN}} - I_{TEG} + \frac{\Delta I_L t}{t_{ON}} \right) V_{TEG} dt = P_{TEG}(1 - D)t_{sw} \end{aligned} \quad (6-50)$$

In Eq. (6-50) V_{TEG} is assumed to be constant, whereas in practice it decreases every switching period. The total stored energy in the Voc capacitor is illustrated by:

$$E_{C_{VOC_TOTAL}} = E_{C_{VOC_0}} - n_{cycle} E_{C_{VOC_CONV}} = \frac{1}{2} C_{VOC} V_{C_{VOC_TOTAL}}^2 \quad (6-51)$$

where, n_{cycle} is the number of periods when the Voc transistor is in the open condition.

Another fractional open circuit voltage measurement can be achieved over the resistors instead of the capacitor and is illustrated in Fig 6.34 [62]. A sampling period of 100ms is applied into the system to measure the open circuit voltage of implementation and it disconnects the source from the converter for $2\mu s$. The disadvantages of this system is the constant power loss at the sampling resistors which continuously occurs in the system.

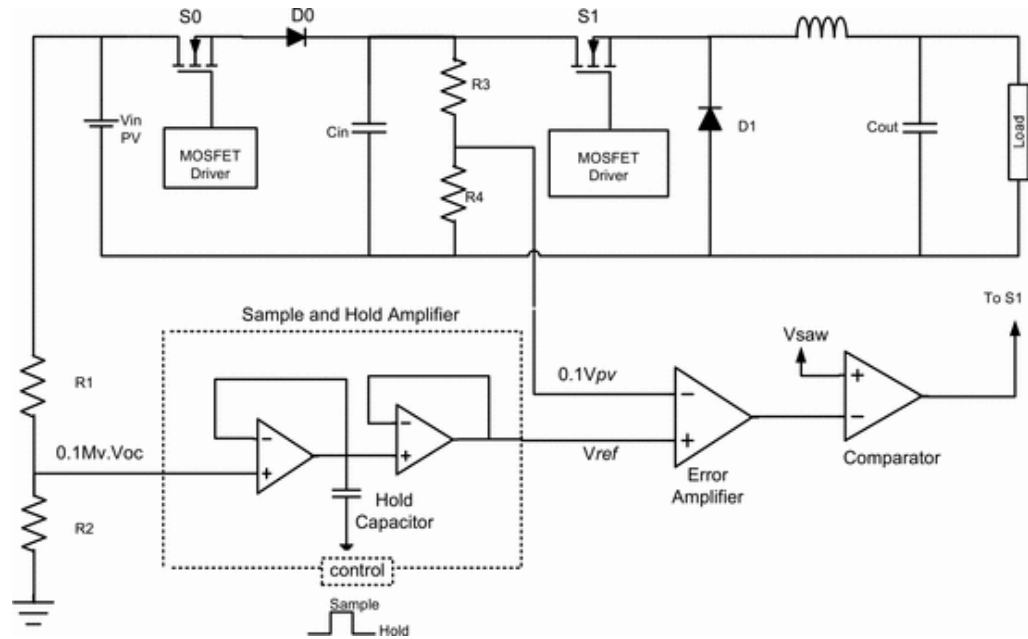


Figure 6-34 Fractional open circuit voltage measurement and DC-DC converter.

6.4.3 Conclusion

The experiment and analysis of both online adaptive perturb and observe MPPT methods and the offline incremental conductance MPPT method are investigated in this section with the advantages and disadvantages of their application. Analysis of these two methods shows that the offline IC MPPT method provides a better efficiency in reaching the maximum power point, however the computational complexity and disconnection between the TEG and the converter, which causes power losses, are the two main drawbacks of this system. The online adaptive perturb and observe method overcomes the step size problem by adaptation and the disconnection problem by an online measurement method. However, the current oscillation around the MPP and the lower efficiency in reaching the MPP than the IC method are the two main drawbacks of this method. In addition to MPPT analysis, the H-Bridge converter structure

analysis provides input and output current measurements with less additional components due to the filter units on the input and output sides. Therefore, an online adaptive P&O provides less power loss in the system. A microchip PICKIT unit is used to illustrate the H-Bridge DC-DC converter control signals with a 78 kHz operating frequency.

Chapter 7 Thermoelectric Generators Design and Installation

The thermoelectric test rig units are improved in size, power level and thermal efficiency within the implementations of test rigs. The initial assembly and improvement is initiated with a single thermoelectric generator. In the second test rig, the thermal and power analysis is implemented for the next test rigs, In the third test rig, a half scale power generator unit is designed and assembled, even though it is designed on a half scale, more than 500 W of power is provided with this unit. In light of these three test rigs, the thermally and electrically improved fourth test rig is designed which overcomes many of the obstacles faced in the previous three test rigs.

7.1 Single Thermoelectric Generator

Test rig 1 is designed to understand the thermoelectric module characteristics and the outputs which leads to a comparison of the simulation values and a large scale unit TE generator's analysis.

7.1.1 Single TE Module Generator

The single thermoelectric module is used to generate power in the first test rig to understand the basic operation of a large unit TE generator. The volume of the initial test rig is decreased significantly which can be seen in Fig 7.1. An oil tank, which was used for heating in the initial experiment, is replaced by a thin film heating system. The large amounts of insulation foam of the previous experiment are changed to a high temperature resistant small size plastic material.

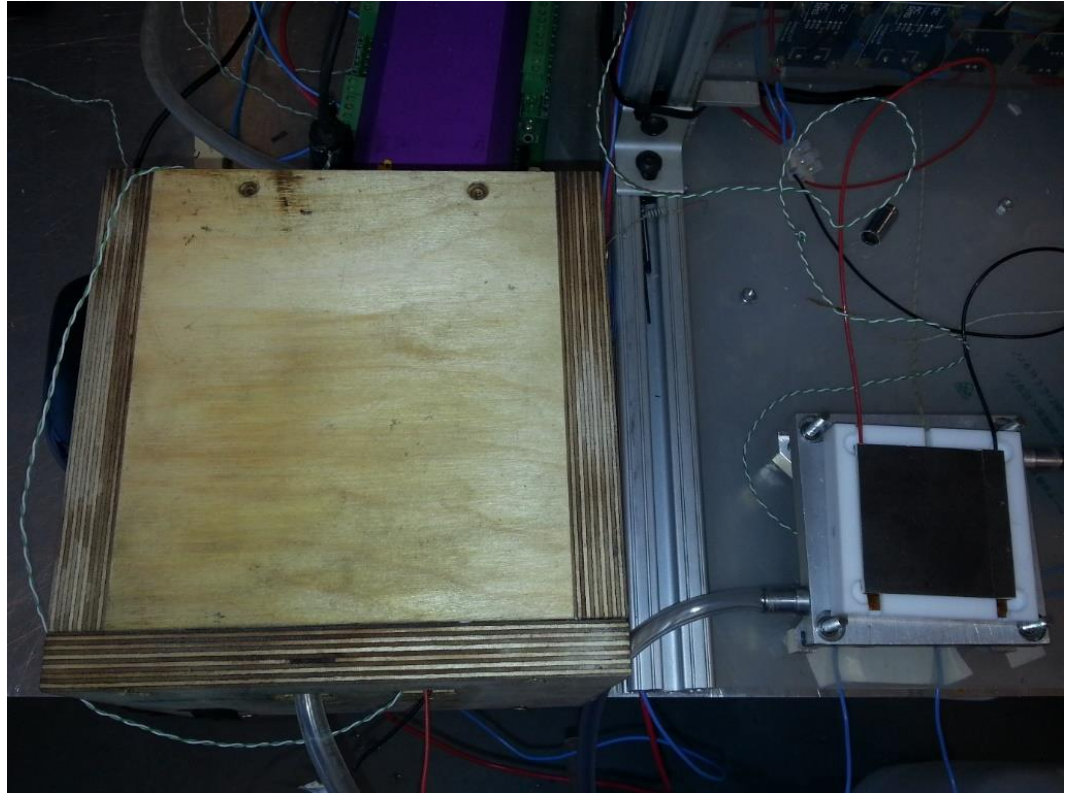


Figure 7-1 Previous and current single TE module generators.

Secondly, the data sensing ability is increased vitally to observe and understand the system at every point of view, thus the experiment is analysed successfully to improve efficiency. In the present experiment, a current measurement and a variable load is implemented to the system in addition to an open circuit voltage gauge, which was the only electronic measurement part in the system. In addition, flat temperature sensors are affixed to both the cold and hot side of the module, the flat shape of the thermocouple sensors provides minimum disturbance to the heating and cooling systems, to prevent an efficiency decrement and also a better sensing ability than traditional thermocouples.

Lastly, in addition to replacements of the previous equipment, supplementary sensors, flow sensors and force sensors, are placed into the test rig. The flow

sensor is applied to the system for analysing the effect of the flow rate to the output power of the generator. The force sensor is also added between the thermoelectric module and the cooling plate to observe the impact of the force for the most efficient installation, especially for heat transfer. In addition to these, all the equipment is mounted on to panel for mobilised and flexible monitoring for the current and following test rigs.

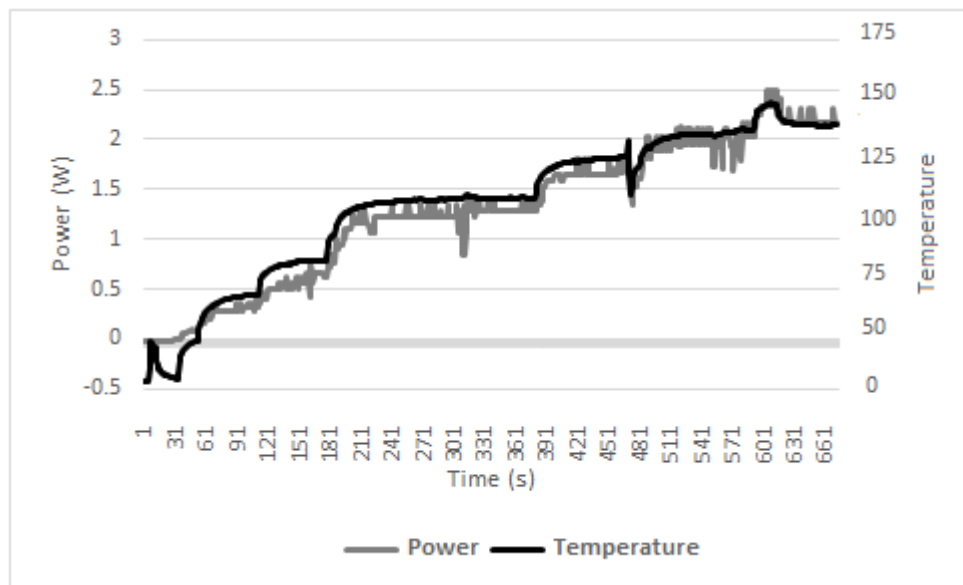


Figure 7-2 Power output and hot side temperature in time.

Figure 7.2 shows that the test rig can generate 2.5 Watts of power when the temperature difference is less than 150°C and the cold side temperature is more than 60°C, with an applied load of 0.5 Ohms. The generated power in the test rig is similar to the datasheet value, which is obtained with a 0.26 Ohm matched load. In this test rig, different load resistances are applied into the system in order to observe their effect on the results. The results demonstrate that the matched load values are very low and dissimilar at the varying temperature differences.

One of the purposes of the test rig is the comparison with the simulation results and understanding the reasons for variances. As a result of this comparison, the most effective reason of this deviation is the difference in temperature between the junction and the outer surface of the ceramic. An improvement on this variance is going to be achieved in further works by replacing the ceramic surface with a carbon fibre material, which will happen in collaboration with the material science department.

One of the understandings of the electrical parts is that when a temperature difference is applied to the system, one of the placed TE modules is current driven, which means current increment is higher than voltage increment. In light of this understanding, the best connection of the multiple current driven TE modules generator is found to be in parallel, in order to keep the voltage constant and produce more current. A disadvantage of the high current system is the requirement of high power electrical components which can cause increase in the volume of the device.

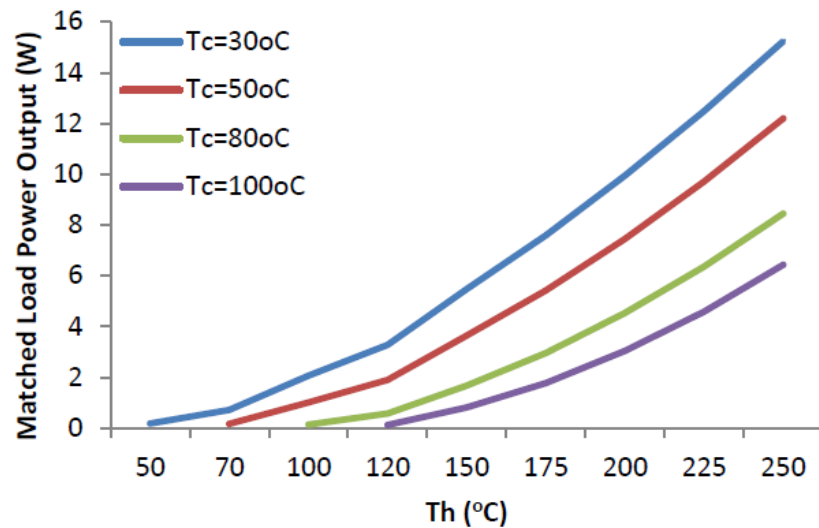


Figure 7-3 Manufacturer TE power output measurement. [63]

Another understanding of the generator system is the importance of the cooling part; power output values at different cooling temperatures are shown in Fig. 7.3. To keep the cooling plate cool, it is not enough just to transfer heat from the junction to the cooling plate. In this test rig which is shown in Fig. 7.4, a temperature difference between the ceramic outer surface and the cooling plate surface is as high as 30°C. To decrease both the hot and cold side temperature variance between the heating and cooling system, a graphite sheet is applied to both sides and the power generation is increased up to 1 watt, which is 25% of the produced power at a less than 100°C temperature difference. The last understanding of the test rig is the heat distribution. Different points are measured during the experiment and the central region of the TE is heated more than corner regions. This difference causes a power reduction because of the lack of heat distribution to every point equally. The spreading of heat is boosted by the applied graphite sheet.

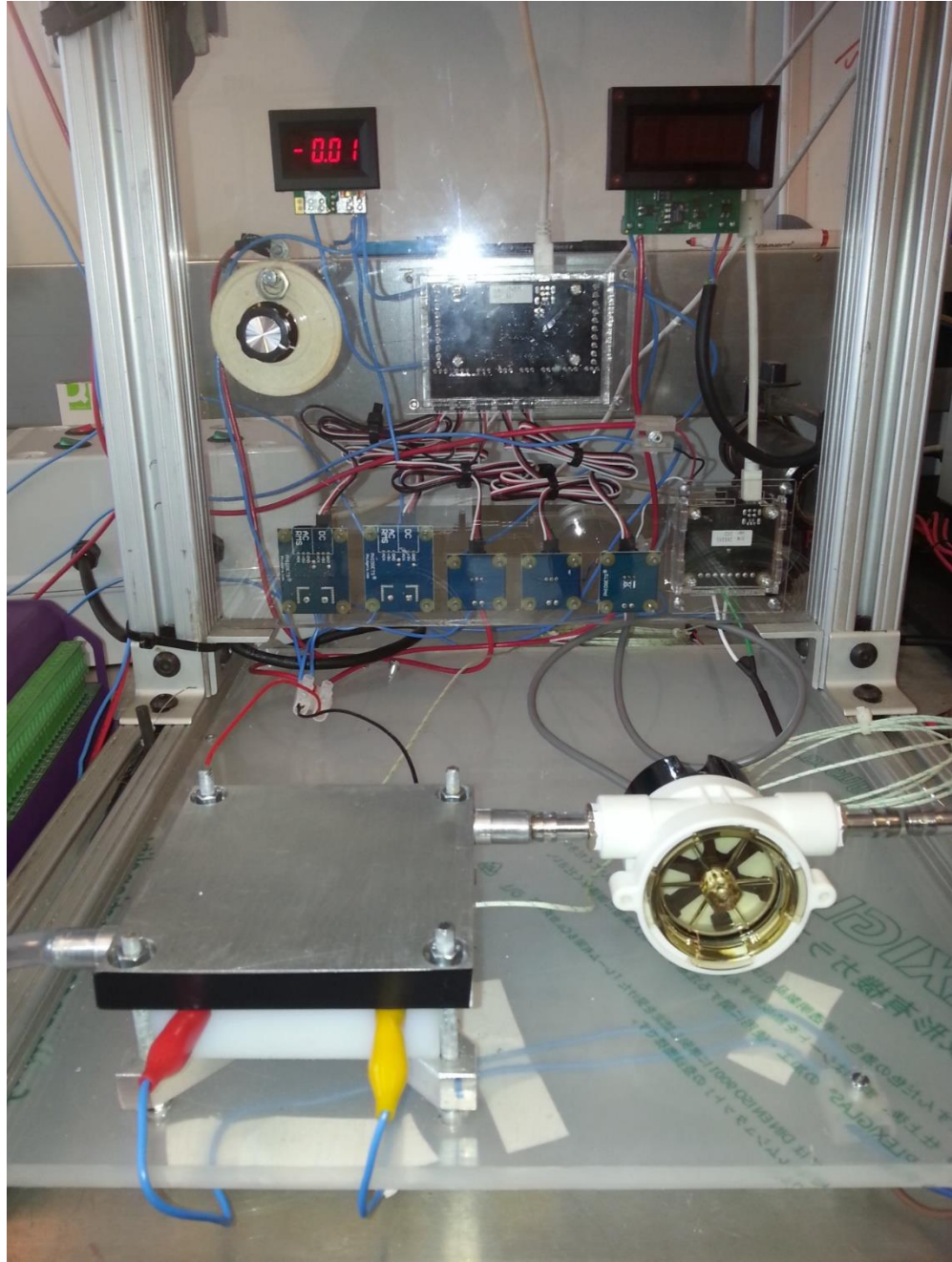


Figure 7-4 Single TE module generator and data acquisition unit.

In Fig 7.5, the electrical connections of the sensors and cooler are illustrated. The measured parameters, which are the temperature values of both sides, the current and the voltage output of the TEG unit, are provided for both the transient and steady state characteristics of a single TEG. The measured parameters are

compared with the manufacturer's data and due to this comparison it is observed that the power output at same temperature gradient of both test rig 1 and the manufacturer's data are similar.

7.1.2 Flow Charts of the Test Rig

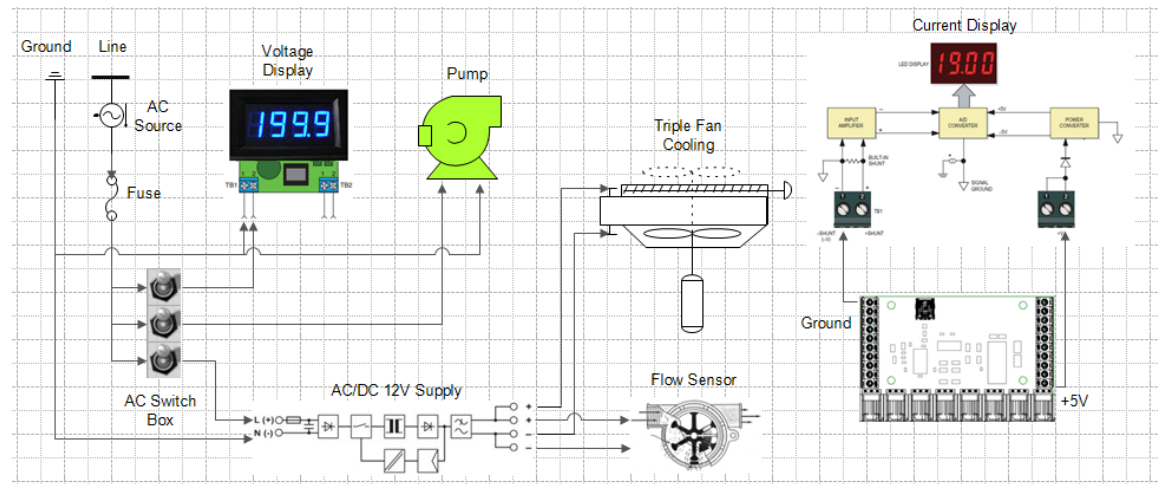


Figure 7-5 Electrical connection design for data acquisition and cooling unit.

As illustrated in Fig 7.6, the closed loop cooling system is applied into the TEG unit where the cold side water is cooled by a triple fan cooler. The reason of choosing a triple fan cooler is that it is easy to implement into the system and the cooling power reaches the demands of a single module generator system. In addition to the cooling system, a flow sensor is applied into the generator to analyse the response of the generator at different water flow capacities.

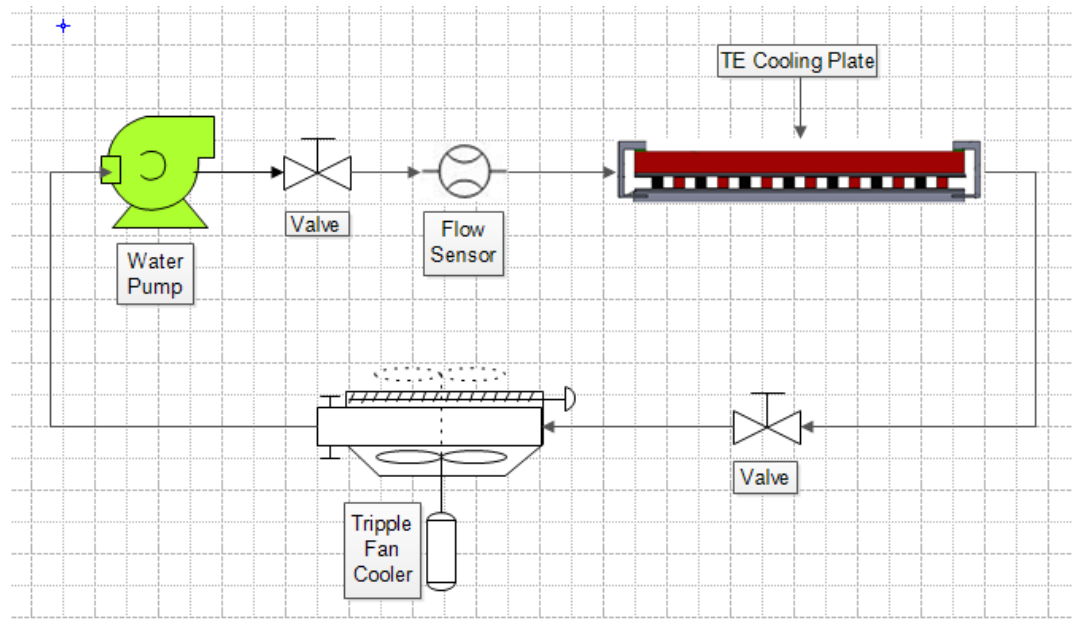


Figure 7-6 Closed circuit cooling water circulation.

In Fig 7.7, the whole TEG generator unit is illustrated, an applied rheostat in the TEG unit provides data on the power output variance and the response at different load resistor values. The measured parameters through a single TE generator are monitored through an interface kit within the designed FLOWSTONE data acquisition unit.

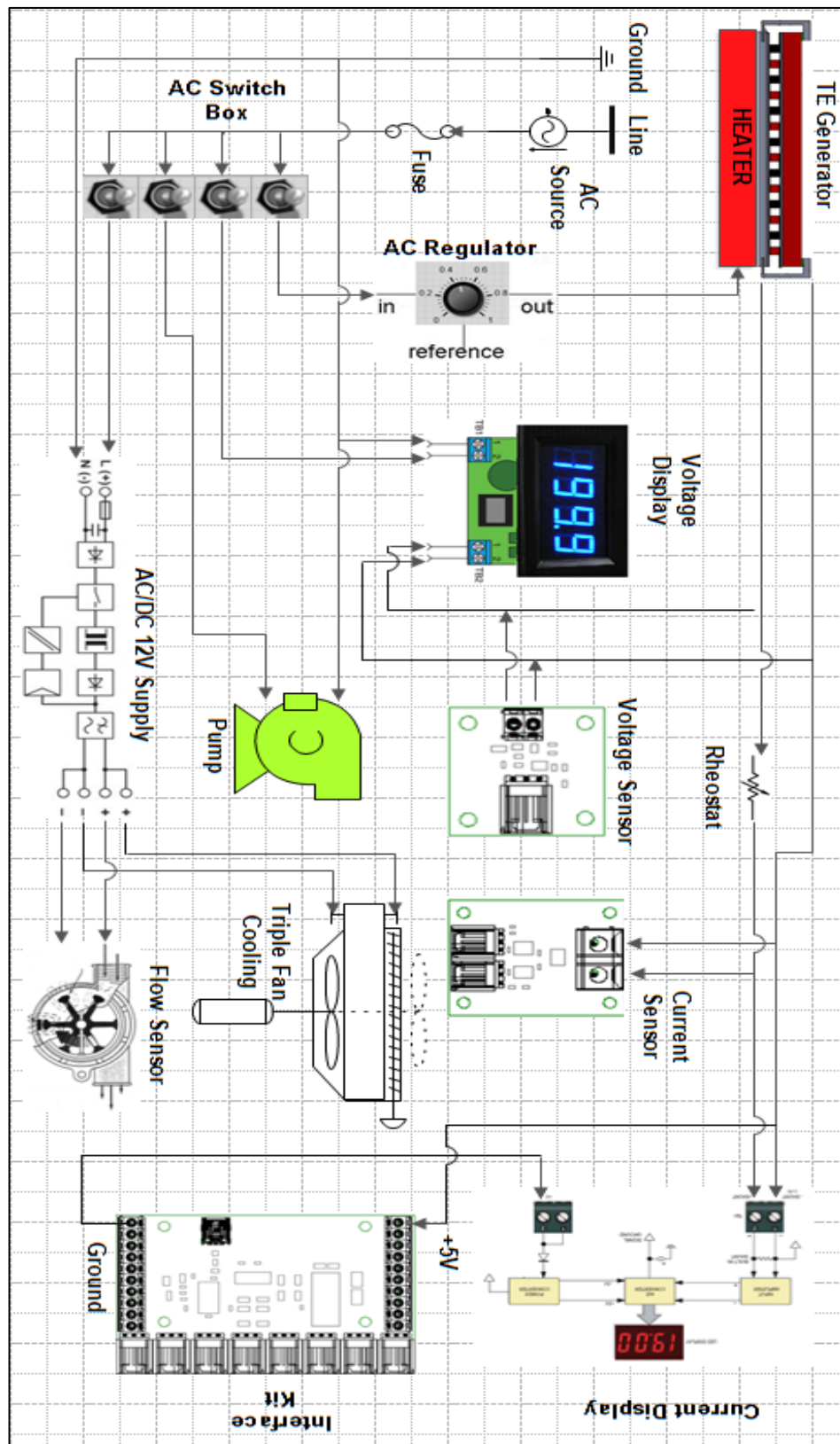


Figure 7-7 Electrical connection design of TEG.

7.1.3 Data Acquisition Unit Design

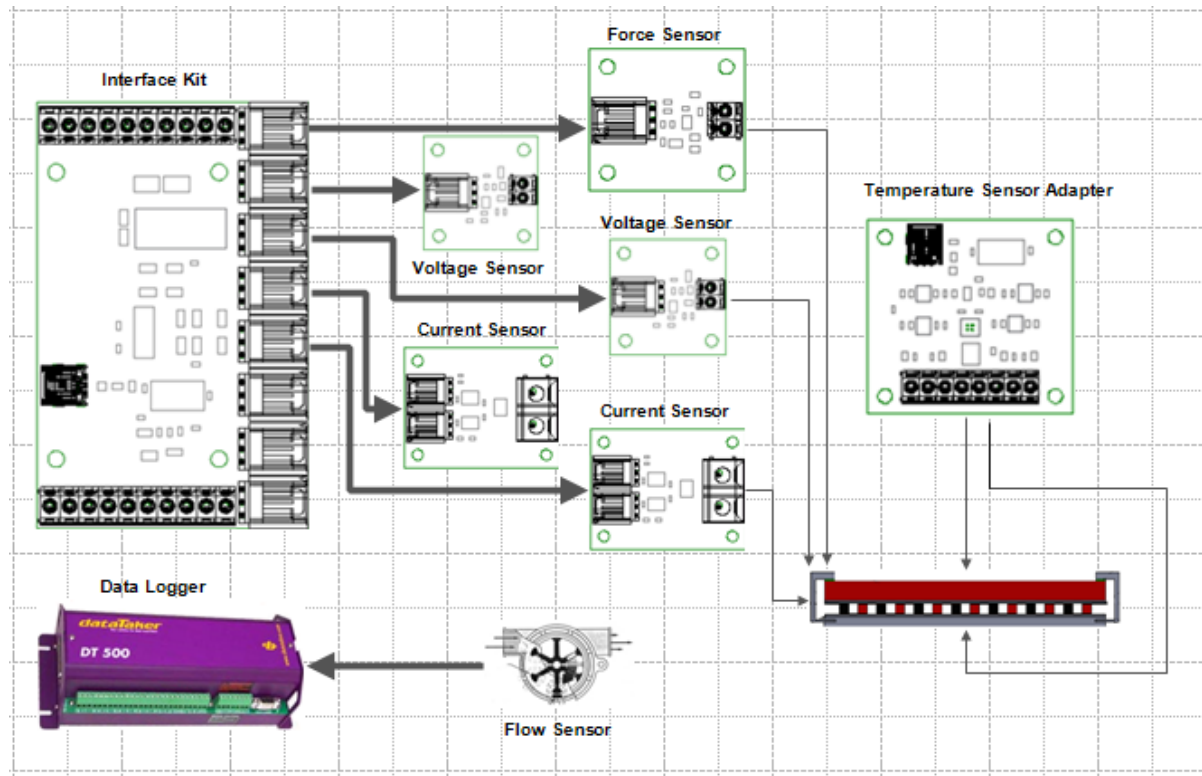


Figure 7-8 Data acquisition unit design and connections.

In the data acquisition unit which is shown in Fig. 7.8, electrical measurement values are collected in the interface kit and sent into the designed program in FlowStone. These electrical sensors are divided into two types, one of them is for ratiometric data and the other one is for non-ratiometric measurements. For temperature and flow rate measurements, adaptors are used to log the data.

In addition to the data acquisition sensors, display units are applied to control the accuracy of data logging. Also, a DataTaker is applied into the system as a PWM frequency counter. The purpose of the designed data acquisition unit is to provide a small volume but accurate power generator system in the main TEG design.

7.2 Experimental Data and Installation of Quarter Scale Test Rig

7.2.1 TEG Components and Parameters

The TEG prototype is designed and installed to allow observation and analysis of its characteristics in varying operating situations. The measured output data and performance of the prototype illuminates the main scale TE generator which has a basic establishment and methodology. Developments of the installation are identified and incorporated into the main TE generator.

Cartridge heaters, thermoelectric modules, stainless-steel plates, heat pipes and a perspex shell comprise the TE generator unit. The stainless steel plates which are in contacted with the hot surfaces of the TE modules, are heated by the cartridge heaters, which are placed into the centre of the plates through holes. The installation consists of five plates, three of them are heating plates and two of them are cooling plates. The cooling plates transfer the composed heat via the heat pipes, which are partly in the water tank where the cold water flows and partly in the cooling plate holes. This installation keeps the cooling plates at an approximately constant temperature, however a temperature difference between both ends of heat pipe does occur in the system. A TEM is chosen to be of a low quality for this initial experiment due to the fact that the purpose of the test rig is to estimate the mechanical and electrical losses in the system and realise possible improvements that can be made for the actual generator. Bi₂Te₃ thermoelectric modules are used to generate the power by an applied temperature difference through the cooling and heating plate. The thermoelectric module properties are given in Table 7-1[64].

Table 7-1 Specifications of applied TE module in TEG prototype. [64]

TE Module Name: GM-250-127-14-16	
Matched Load Output Power [W]	6.99
Open Circuit Voltage [V]	10.11
Matched Load Output Current [A]	1.38
Matched Load Output Voltage [V]	5.05
Heat flow through Module [W]	139.8
Maximum Hot Operation Temperature [°C]	250
Maximum Cold Operation Temperature [°C]	175

The thermocouple modules are connected together in the configuration of four in series and four in parallel. While the parallel connections are increasing the current output, the series connections provide a higher voltage output to with the aim of providing a constant battery voltage. The wire connection design is shown in Fig 7.9.

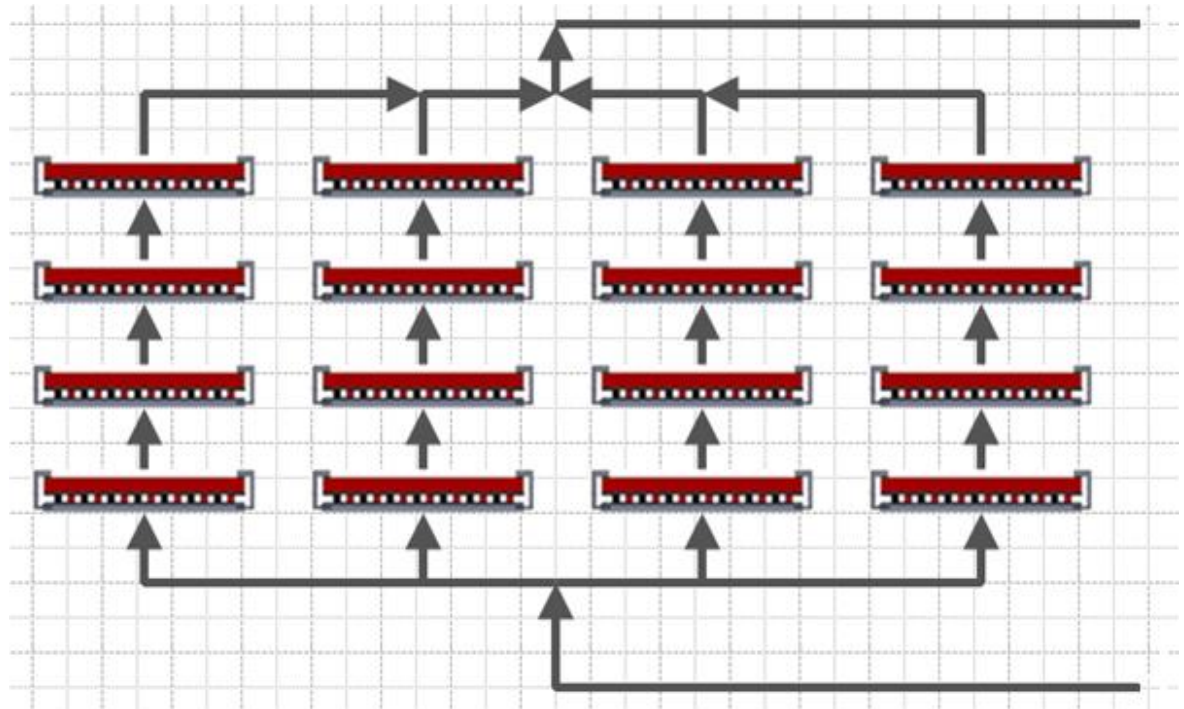


Figure 7-9 TE generator electrical connection.

After wiring in the thermoelectric modules, a variable load resistance and a calibrated current sensor are connected to the TEG output in series and a voltage sensor is applied in parallel to the current sensor and load. Both sensors are wired into the analogue inputs of the Phidgets interface kit 8/8/8 board, which is connected to the pc using sensor cables. The analogue to digital conversion is accomplished by the interface kit.

7.2.2 Measurement Sensors

7.2.2.1 Voltage Sensor

Table 7-2 Voltage sensor specifications. [65]

Voltage Sensor	
Maximum Measureable Differential Voltage [V]	+/- 30
Accuracy [%]	2
Maximum Analogue to Digital Conversion error [%]	0.5

The Voltage Sensor measures the differential voltage between the input terminals and calculates an output based on the proportional difference. For the range of values and conditions being tested, the voltage sensor was able to measure with an accuracy of within 2%. The equation to translate the sensor reading to differential voltage is given by Eq. (7-1) [65]:

$$V_{\text{diff}} = \frac{\text{Sensor Value}}{13.62} - 3637107 \quad (7-1)$$

7.2.2.2 Current Sensor

The ratiometric feature of the ACS712T represents the device gain and te offsets are dependent on the supply voltage, VCC. This property is especially important when using the ACS712 with an analogue-to-digital converter such as the current measurement.

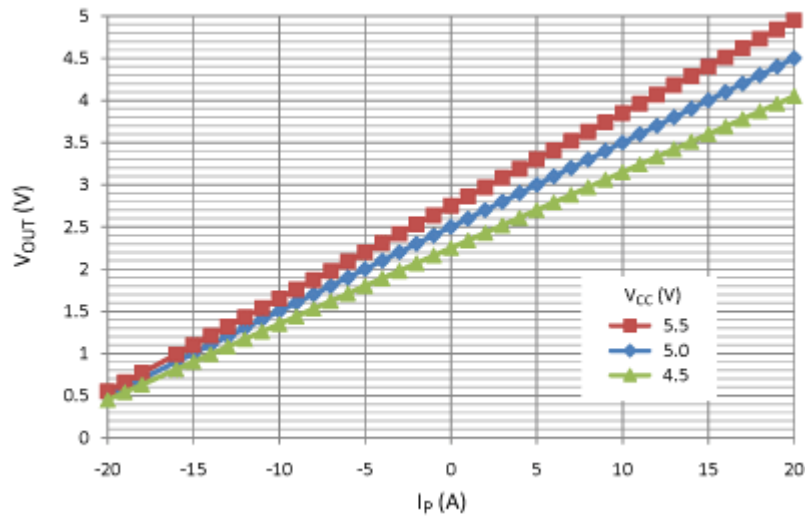


Figure 7-10 Voltage output of current sensor corresponding to supply voltage.

[66]

The ACS712T uses a Hall-Effect method, which is compatible with all electrical currents having both AC and DC parts. The bandwidths are 80 KHz typically. The usage of a 0.1 μ F bypass capacitor between the VCC pin and the GND pin acts like a filter to improve accuracy.

Table 7-3 Specifications of current sensor. [67]

Current Sensor	
Maximum Measureable DC Current [A]	30
Maximum Measureable AC Frequency [kHz]	10
Maximum Supply Voltage [VDC]	5.5
Minimum Supply Voltage [VDC]	4.5
Accuracy (25°C operation) [%]	1.5

Maximum Analogue to Digital Conversion error [%]	0.5
--	-----

The equation that translates the sensor reading to DC current is given by Eq. (7-2) [67].

$$I_{DC} = \frac{\text{Sensor Value}}{13.2} - 37.8787 \quad (7-2)$$

7.2.3 Measurement and Analysis of TEG Prototype

The Flowstone software, which provides a real time calculation and display of the current and voltage values, is programmed for data logging. A serial connected variable resistor which has six settings is used as a load to test the characteristic outputs of the TEG. The settings and equivalent resistor values are shown in Table 7-4.

Table 7-4 Variable resistor setting.

Variable Resistor Setting	External Resistance [Ω]
6	39.0
5	17.2
4	7.2
3	2.6

2	1.5
1	Short Circuit

The hot and cold plate surface temperatures are measured by a K-type thermocouple. The requested cartridge heater temperature is kept constant by a digital temperature controller, which performs PID control via a feedback value of the measured hot side temperature.

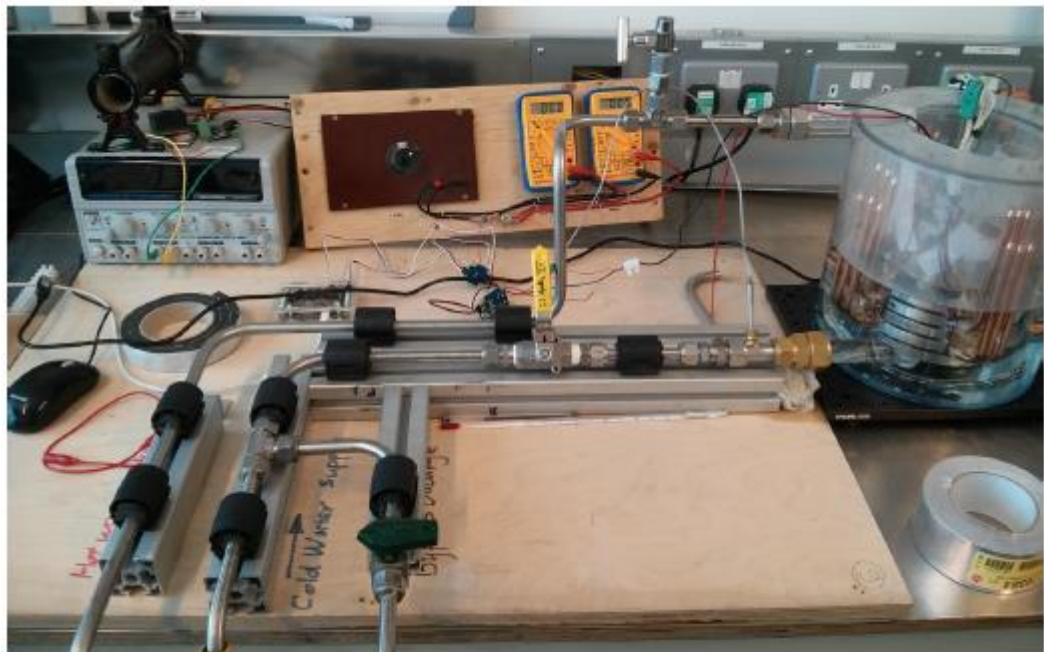


Figure 7-11 Quarter scale (16 module) TEG.

Recoverable heat flux, water flow rate and load resistor are adjustable parts of the test rig. The produced heat flux through the cartridge heaters, which transmit heat by conduction to the heating plates, are present in the TE generator. An angle valve provides control of the water flow rate, which is gauged by using a measuring cylinder. Lastly, the load is adjusted by a variable resistor.

The variant water flow rate conditions, which are given in Table 7.5, are applied to the system when the heater temperature is stable. To understand the effect of the flow rate and to find the matched load resistor value, the cold side temperature is gauged at different flow rates. Initially, the cartridge heater temperature is set to 80°C and the internal resistance of the TEG is measured to be 2.2 Ω . When the heater is constant, different load values are applied to the system at each flow rate condition. Next, the measured heater temperature is increased to the subsequent value and previous measuring system is repeated for all of the hot side temperature conditions.

Table 7-5 Flow Rate Settings

Cooling water flow rate [l/s]
0.080
0.120
0.180
0.210
0.288

The voltage and current measurement data are logged into the program for each of the different conditions. In addition, the outlet water temperature is gauged at each of the different flow rate settings by the thermocouple.

The plotted peak power values, corresponding to the flow rate values when the heater temperature is constant, allows the investigation of the effect of the external resistance. The subsequent measurements for the different heater temperature settings also provide the effect on the hot side temperature. One of the monitored results is displayed in Fig 7.12.

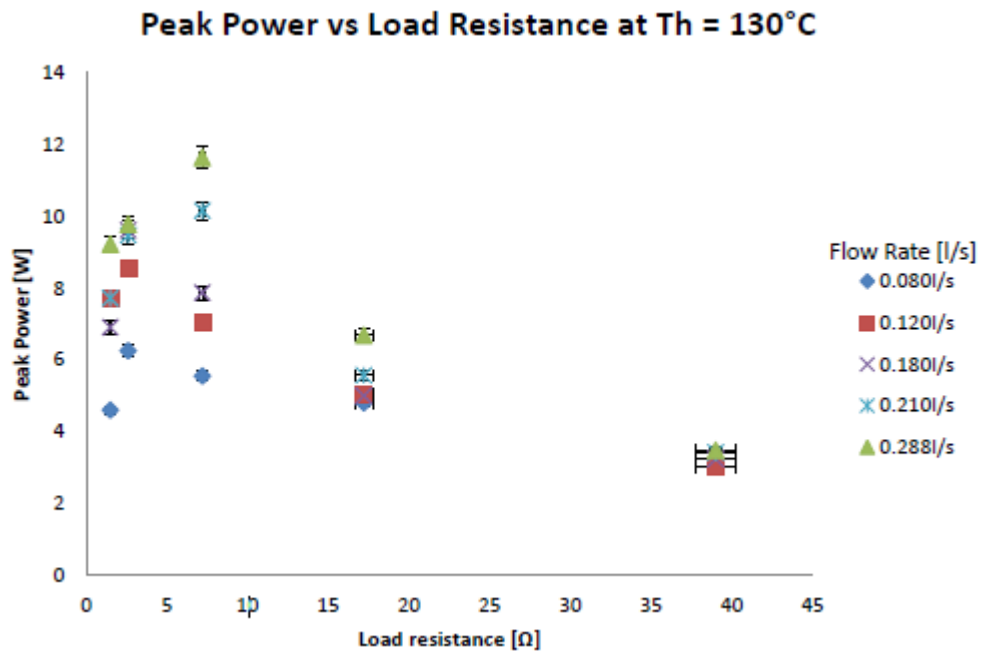


Figure 7-12 Peak power vs. load resistance when $T_h = 130^\circ\text{C}$.

The water flow rate also has an effective role to find the matched load resistor and to obtain the maximum power output. The reason of this effect is that the internal resistance is varying according to the temperature, which means it is temperature dependant and because of that the matched load differs corresponding to the flow rate.

The matched load values at different heater temperatures and flow rate values are shown in Table 7.6. As seen in Table 7.6, to obtain higher power output results the external resistance value should be kept between 0 and $7.2\ \Omega$.

Table 7-6 Matched load at varying hot side temperature and flow Rate.

	Q [l/s]				
Th [°C]	0.08	0.120	0.150	0.210	0.288
80	7.2 Ω	2.6 Ω	2.6 Ω	2.6 Ω	2.6 Ω
90	7.2 Ω	7.2 Ω	2.6 Ω	2.6 Ω	2.6 Ω
100	7.2 Ω	2.6 Ω	2.6 Ω	2.6 Ω	2.6 Ω
110	2.6 Ω	2.6 Ω	2.6 Ω	2.6 Ω	2.6 Ω
120	7.2 Ω	7.2 Ω	2.6 Ω	2.6 Ω	2.6 Ω
130	2.6 Ω	2.6 Ω	2.6 Ω	7.2 Ω	7.2 Ω
140	7.2 Ω	2.6 Ω	2.6 Ω	2.6 Ω	2.6 Ω
150	7.2 Ω	2.6 Ω	2.6 Ω	2.6 Ω	2.6 Ω

The highest measured output power from the TE generator is 12.59W when the hot side temperature is 150°C. It is known that each TE module has a maximum power of 6.99W as stated by the manufacturer. Fig 7.12 demonstrates the maximum power of a thermoelectric module for different settled hot and cold-side temperatures, also as stated by the manufacturer.

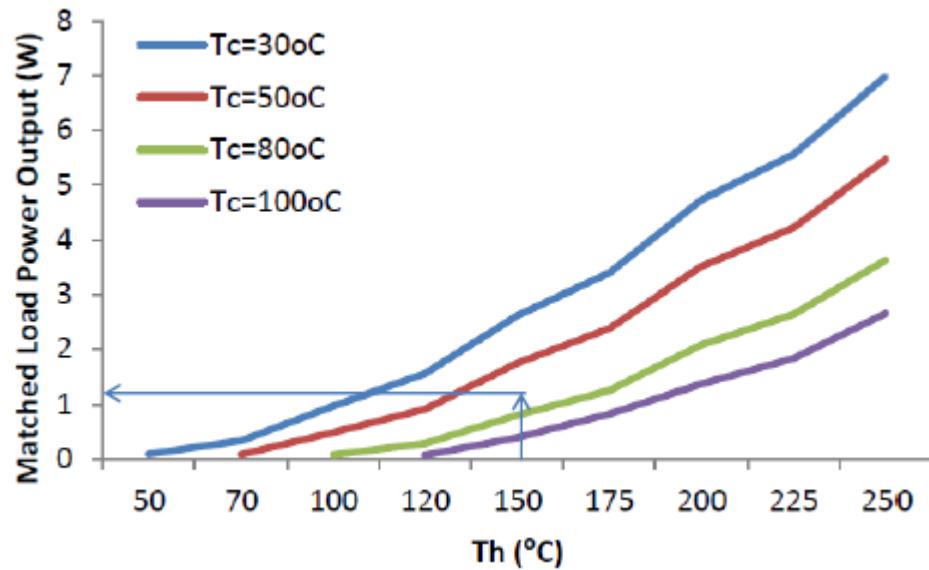


Figure 7-13 Matched load output power vs. hot side temperature for fixed cold sides. [63]

It is specified that the measured power is relatively equal to 1.1W for one TEM at a hot-side temperature of 130°C and a cold-side of 70°C, as seen in Fig 7.13. For a total number of 16 thermoelectric modules, it is calculated that the maximum TEG power is 17.6W. The highest measured power from the test rig approaches 72% of the manufacturer's result. The reason of the variance can be explained by the differences between the applied external resistances and the matched load, the consideration of the same temperature difference for all sixteen TE modules in manufacturer's data, which is shown to be varied in the test rigs for each TE module, and connection losses.

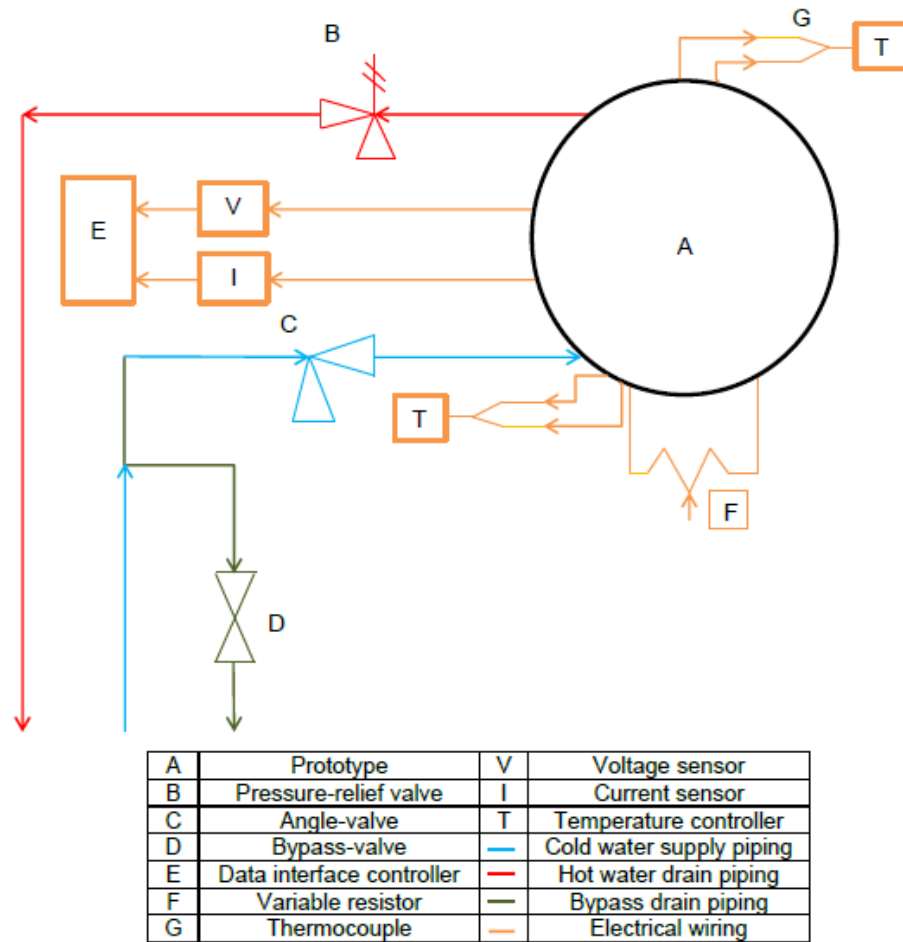


Figure 7-14 Experimental installation schematic.

7.2.4 Designed Data Acquisition and Controller Program

The established software program provides both monitoring and controlling of the test rig equipment such as the sensors and outputs. The interface kit and the temperature sensor adapter inputs are displayed on the main screen. Also the output of the interface kit is controlled by switches to supply power to the system. In addition to these, the established program is designed to log data and save it as an excel file for data analysing.

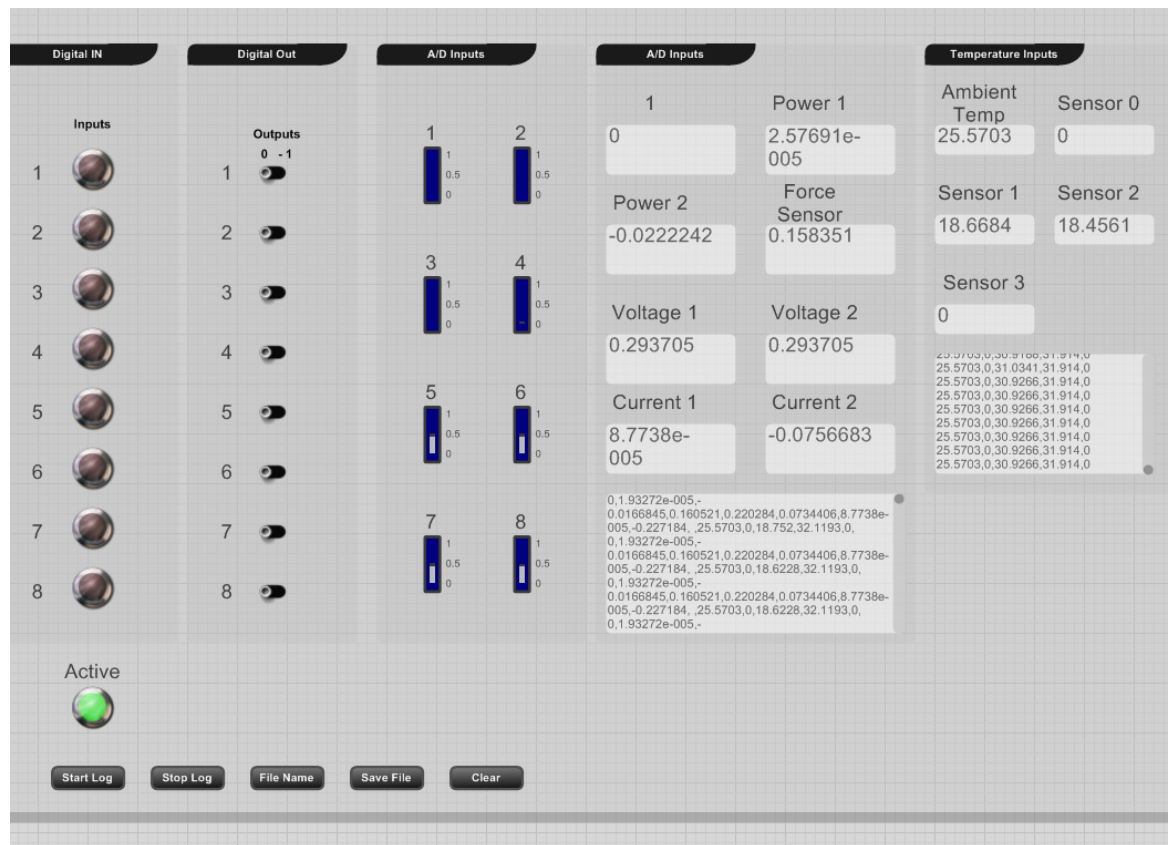


Figure 7-15 Data acquisition display unit.

The current, voltage, force sensor and calculated power are demonstrated on the analogue input module simultaneously. The hot side and cold side temperature of the TE and the ambient temperature are displayed on the temperature input module. The digital output module is designed to control each output by switches such as sn ammeter power supply. The incoming data is displayed on the digital input module and activates each led according to the input port.

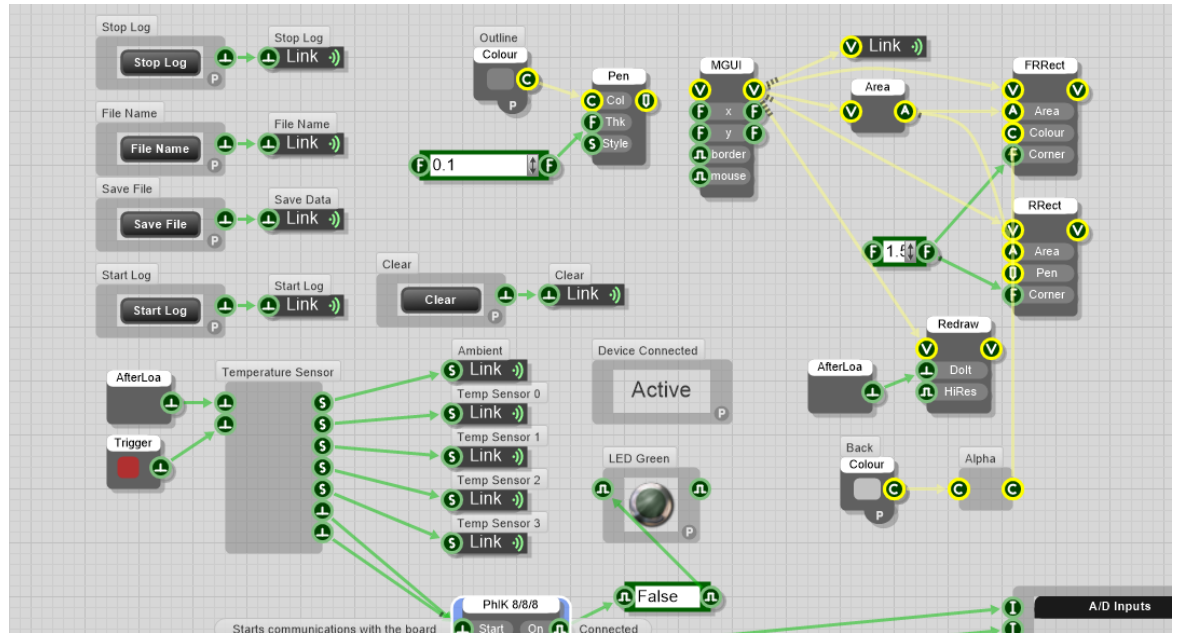


Figure 7-16 Module design of sensors and inputs.

All of the data transfer between the test rig and the computer is simplified by a prepared GUI system. Each group of ports is established by the modules and programmed with control and monitoring capabilities. The wireless controls between the modules are applied to program in order to decrease the complexity. The FLOWSTONE electronic software program, which controls data acquisition unit, is used to establish the data transfer and modules.

7.3 Experimental Data and Installation of Semi Scale TEG

7.3.1 Test Rig Installation

The semi scale TEG test rig consists of several sub units, the heating unit, air blower unit, cooling unit, data acquisition unit and TEG unit.

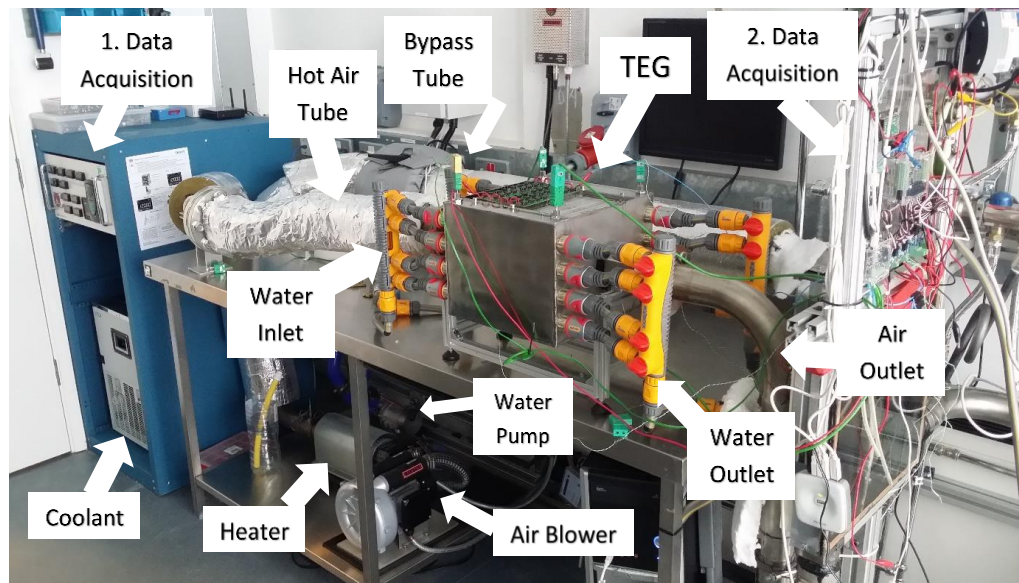


Figure 7-17 Semi scale thermoelectric power generator.

To simulate automotive performance accurately, the components are chosen to be similar to an actual automotive system, however due to safety concerns, hot air is used in the test rig instead of actual exhaust gas. In addition, instead of a combustion engine, an air blower and heater are used in the test rig, which can provide up to 900°C hot air flows through the tube. An actual exhaust pipe system is also implemented into the system with thermal insulation to obtain accurate results the during test, additionally a bypass tube is placed into the system, which is used to eliminate system break down when extreme conditions occur. Under the consideration of the commercial purposes of this project, a DC motor controlled butterfly valve system is designed and realised at a small scale with a control mechanism by using an Arduino board and a DC motor which operates between 0° to 90°. the control mechanism is designed to operate according to the pressure, temperature and mass flow rate.

The test rig coolant system, which can even operate at 0°C, and the closed loop system is more advanced than the actual vehicle cooling system due to the need to analyse the cooling systems effects, however the water pump, which is commercially in use, is chosen according to an actual automotive system. In addition, on the TEG side the coolant water is applied into the heat exchange unit at four levels instead of one to improve the heat flux efficiency.

The data acquisition units are placed on two sides, the first unit which is used for the temperature measurements is integrated with the hot air heater and pump control system to shut the system down if it reaches extreme conditions. In addition to the temperature control system, a voltage measurement system is also installed in this unit, which provides online data measurement through an internet connection for a remote control mode, which is shown in Fig 7.17. the second data acquisition unit is used for the thermal and electrical measurements, to obtain data simultaneously within the efficiency and power production, which is determined in section 7.1. In addition to the measurement units, the data acquisition unit also has variable resistor, which provides the actual performance of the power when a load is applied.



Figure 7-18 Coolant and first data acquisition unit.

A novel TEG electrical protection unit consists of bypass and blocking diodes and is designed for two purposes. The first one is to prevent a short circuit fault at each layer, which can occur in other layers or from the external side, this protection is achieved by the blocking diodes which are placed at the positive side of the TE generator in series. The second one is achieved by the bypass diodes which are placed parallel to each couple of TE modules. The bypass protection method allows the system to keep generating power accurately even if any TE module becomes an open circuit in the failure condition, such as breaking or connection losses due to a high temperature. This protection method

is necessary in commercial applications which are closed systems and difficult to fix if a problem arises. The bypass and blocking diodes are illustrated in Fig 7.19.

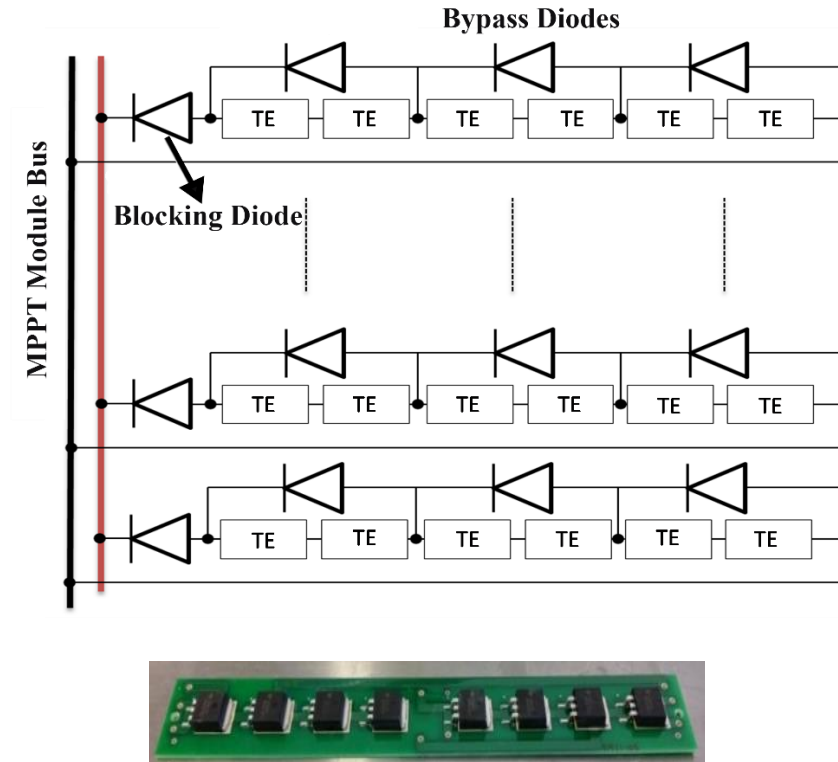


Figure 7-19 Smart bypass and blocking diode circuit for two segments of TEG.

In Figures 7.19 and 7.20, a schematic diagram and the signals of the smart diode are illustrated and the principle of smart diode is determined as follows:

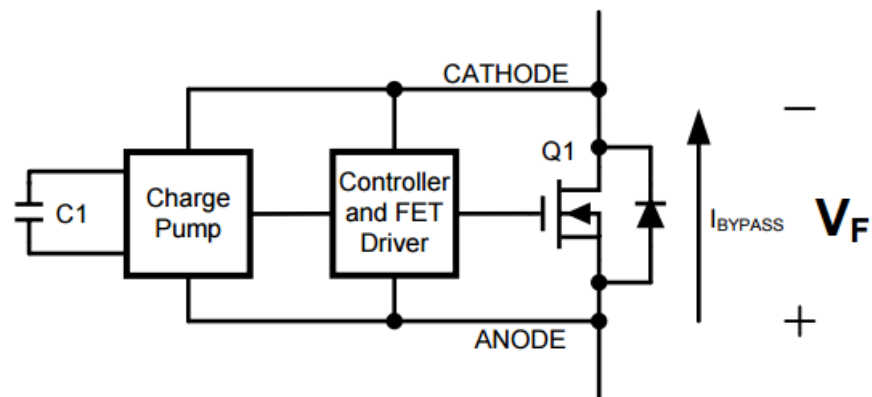


Figure 7-20 SM74611 Block Diagram. [68]

From t_0 to t_1 :

When the thermoelectric module in the TE generator becomes an open circuit, the FET Q1 becomes open and the bypass current flows through the body diode of the FET as shown in Figure 7.19. the bypass current produces a voltage drop (VF) across the anode and cathode terminals of the bypass diode. During this time, the charge pump section is active and it charges capacitor C1 to a predetermined voltage level.

At t_1 :

The charge pump becomes disabled when the capacitor voltage reaches the pre-set voltage amount and the stored energy in the capacitor provides the power to the controller unit.

From t_1 to t_2 :

The bypass current flows through a low resistive FET therefore the power loss at the diode decreases significantly and during the flow over the FET, the capacitor supplies power into the controller unit while the charge pump stays passive.

At t_2 :

The capacitor discharges its energy and reaches a minimum pre-set voltage value therefore the FET becomes open again and the current flows through the body diode by causing a 0.6V voltage drop across the diode terminals.

In conventional p-n junction diodes and Schottky diodes, this high voltage drop occurs continuously but in a smart diode it only occurs during the capacitor charging periods, which is shown in Fig 7.20. Due to a lower forward voltage value, which is only 26mV, the smart bypass diode has a lower power loss than other ordinary diodes which generally have a 0.6V forward voltage.

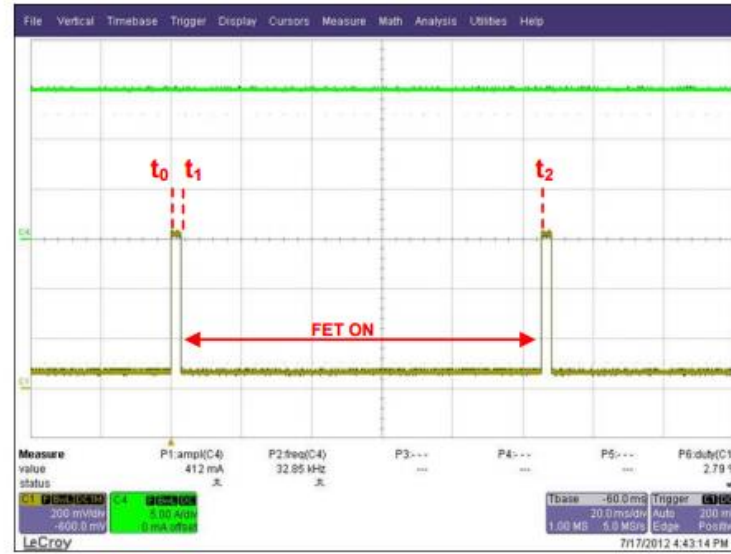


Figure 7-21 Anode to cathode voltage with $I_{BYPASS}=15A$ for smart diode. [68]

7.3.2 System Configuration

In the third test rig, a half scale of thermoelectric generator unit is constructed with a size of 20 cm width, 30 cm length and 20 cm height. This generator consists of 10 layers and 66 thermoelectric modules and it is designed in rectangular shape to allow easy implementation, including the heat exchanger unit, which is illustrated in Fig 7.21. Due to the installation of a generator, the heat transfer on the hot side is in direction of gas flow.

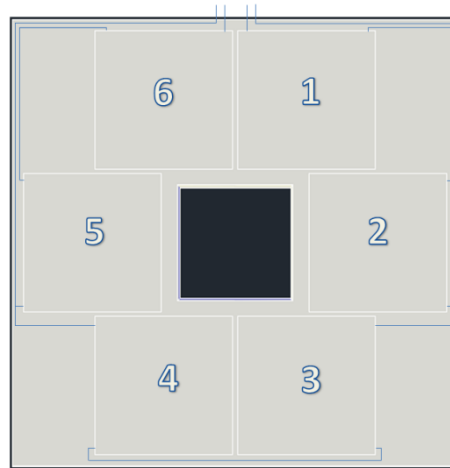


Figure 7-22 TE placement and connections.

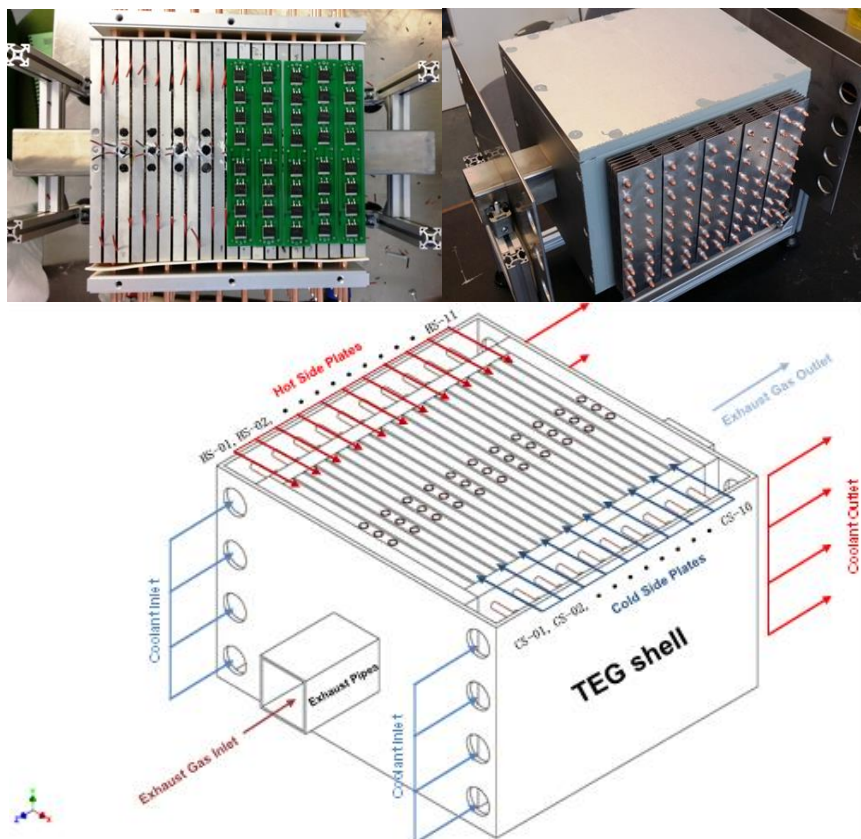


Figure 7-23 Design and installation of TE power generator.

The TEG Installation is composed of segmented thermoelectric module packs which are sandwiched between hot and cold plates to generate power due to a temperature difference. Each layer consists of 6 TE modules (63.5mm L x 63.5mm W x 4mm H) which are connected to each other in series as shown in Fig 7.20. In the heat exchange unit, heat pipes are implemented into system and placed heat pipes which take the place of the fins stack components, provide efficient thermal conductance by transferring the heat from the exhaust pipe to the hot plates of the generators. In the cooling part, the fin plates are implemented to the heat pipes, which provide a very low and almost constant coolant temperature at the cold side of the TEG, to increase the heat flux capabilities. The fin plated heat pipes on the cold side, which draw heat from the TEG surface into cooling system, are shown in Fig 7.22.

7.3.3 Dynamic Heat Transfer Enhancement by Heat Pipes

The hot side and the cold side of the TEG layers are monitored by an infrared camera, as shown in Fig 7.23 while the system is in operation, to prove the thermal efficiency of the system as an addition to the temperature sensor measurement.

Table 7-7 Experiment on proof-of-concept prototypes.

Operation condition	Ranges	Notes
Heated Air Temperature	300 °C ~ 550 °C	Varied by PID control

Air flow rate	650 L/min	Varied by frequency control
Coolant Inlet Temperature	20 °C ~ 50 °C	Coolant circulated by water chiller

As observed while monitoring the system, the cold side plates of the TEG are constantly cool, which improves power generation significantly. In addition, the hot side temperature of the TEG is increased to 65°C in five minutes which is quite efficient and quick.

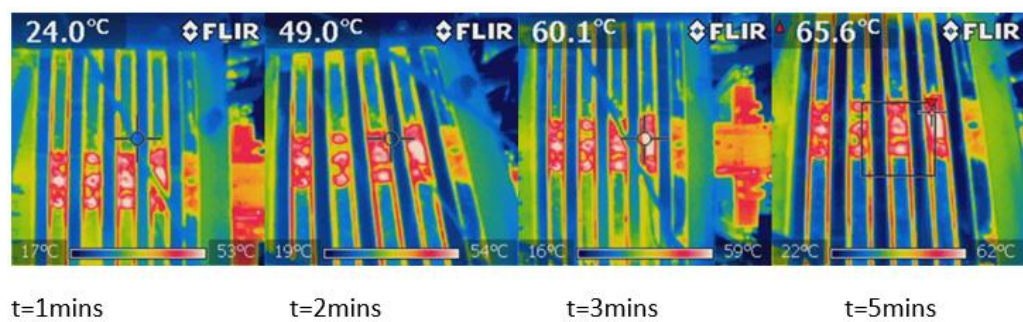


Figure 7-24 The temperature changes at starting mode of exhaust heating.

7.3.4 Transient Thermal Response of TEG

The temperature measurement of the TEG is accomplished to understand and analyse the thermal response of the TE generator. The transient temperature measurement is accomplished in 4 stages.

- The water cooling system is turned on initially to build up and obtain a uniform cool temperature on the cold side of TEG.

- The air blower is initiated after 15 mins of coolant temperature built up, the air blower flow rate is set to 650L/min.
- At 20th minute, the air heater is switched on and set to 500°C at the exhaust inlet. This process is continued for 30 mins
- Lastly, the air heater is turned off while keeping the coolant system on to protect the system and to decrease the system temperature to the coolant temperature

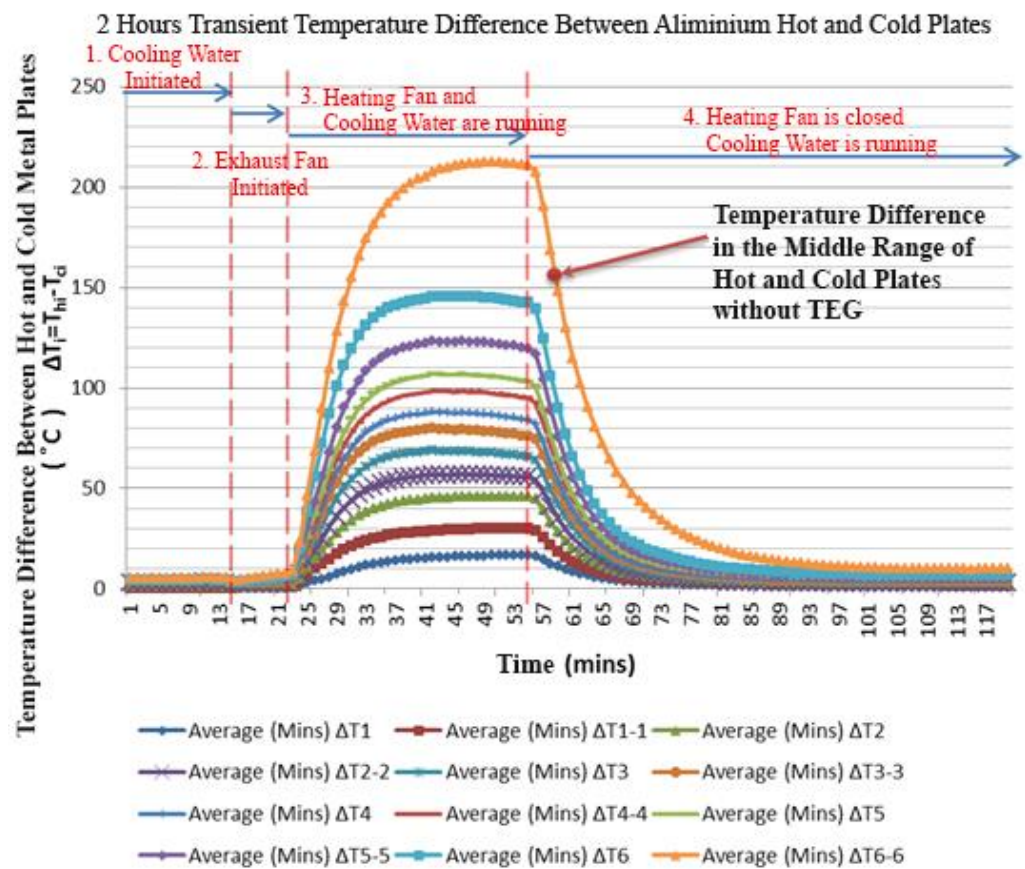


Figure 7-25 Transient thermal performance of each TEG modules.

The temperature differences between the hot and cold sides of the TE generator are varying at each segment, as shown in Fig 7.24. One of the segments which was left without any TE modules to analyse the system, had a 220°C temperature

difference between its hot and cold plates. In the segments containing TE modules, the temperature difference varies from 20°C to 150°C. While the maximum temperature gradient is 150°C on the TEG side, the observed 220°C temperature gradient without a TEG indicates that the heat flows across the TE modules into the cooling water, yet it continues to produce power. A single Hi-Z 20 TE module can produce 12.7 Watt at $T_h=200^\circ\text{C}$ and $T_c=50^\circ\text{C}$ according to the datasheet, therefore the first layer can produce 76 Watt at the matched load by itself. Thus, the obtainable total matched load power is 572 Watt according to each layer's temperature gradient which is given in Table 7-8 when the unevenness of surfaces which cause contact resistance is neglected.

Table 7-8 Temperature gradient of each layer.

ΔT_1	ΔT_2	ΔT_3	ΔT_4	ΔT_5	ΔT_6	ΔT_7	ΔT_8	ΔT_9	ΔT_{10}
150°C	125°C	110°C	100°C	90°C	80°C	70°C	60°C	45°C	30°C

Another experimental measurement of the third test rig is completed by measuring the Hot Air Temperature, Heat Input Power, Coolant Power and Coolant Temperature. In addition to the thermal measurements theoretical power generation is also plotted which shows that around a 3500W power generation can be obtained in ideal conditions.

Table 7-9 Transient Experiment operating parameters.

Hot Air Inlet Temp	Hot Air Outlet Temp	Cooling Water Inlet Temp	Cooling Water Outlet Temp	Fan Flow	Experiment Duration
600°C ± 10 °C	200°C to 300°C	5°C	30°C to 50°C	650 L/min	2 Hours Transient

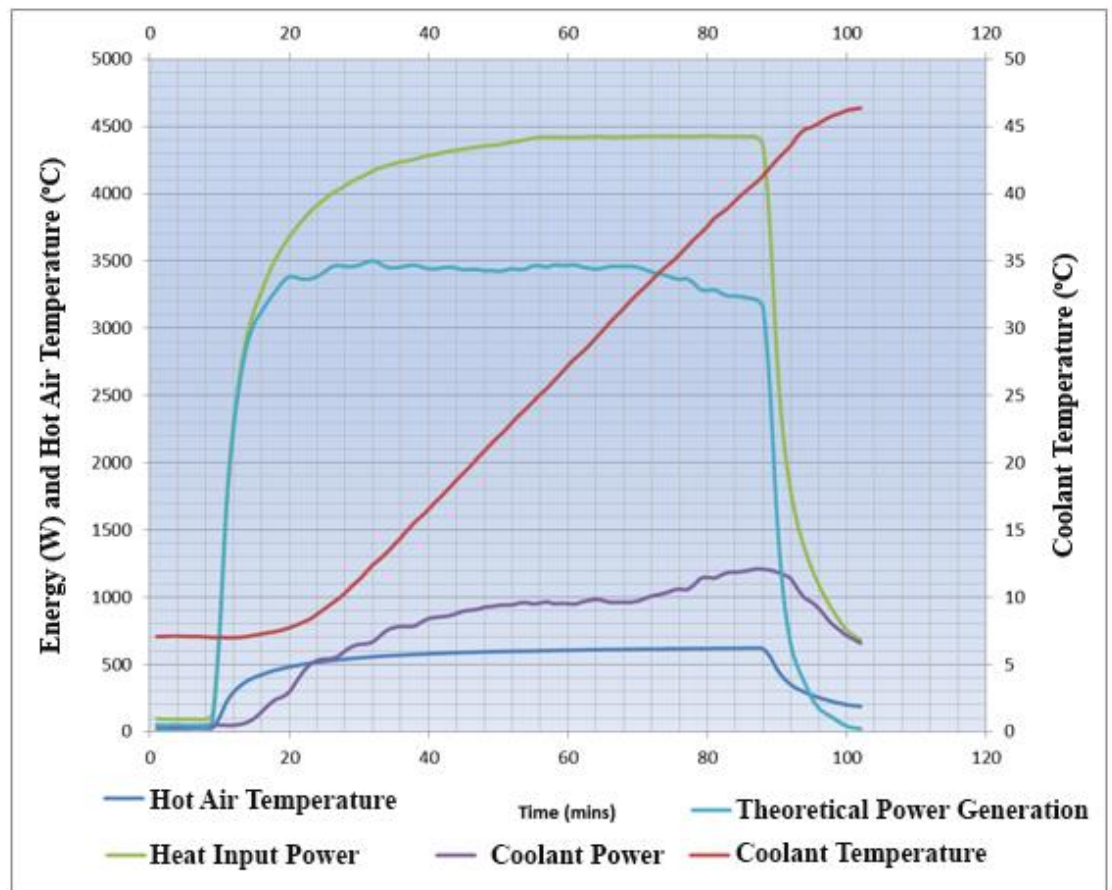


Figure 7-26 Experimental measurement of test rig and theoretical power generation.

7.4 Fourth Test Rig Design

7.4.1 Emission Test Data and Actual Engine Thermal Efficiency

According to the actual values which are provided by the manufacturer, the emission and thermal efficiency are analysed to apply into the test rig experiment. The parameters are obtained at the fully load condition and at different engine speeds, which vary between 1000rpm and 6000rpm, as shown in Table 7-10 and Table 7-11.

Table 7-10 Design parameters and engine thermal efficiency calculation results.

Rotating Speed (RPM)	Average Temperature of pre-catalytic converter (K)	Temperature Before Catalytic Converter (K)	(CFD Model) Mass Flow (Kg/s)	Muffler Front Temperature (K)
1000	841.7	653.3	0.00279780	594.1
2000	986.7	857.3	0.00729235	811.1
3000	1031.7	916.3	0.01164311	837.6
4000	1089.8	993.4	0.0149856	910
5000	1119.4	1057.1	0.0197573	1013.3
6000	1133.1	1077	0.0229319	1041.2

Table 7-11 Design parameters and engine thermal efficiency calculation results.

(CFD Models) Mass Flow (With Silencer) (Kg/s)	Useful Energy (kW)	Fuel Consumption (Kg/h)	Total Value of Combustion Heat at Standard Gasoline (43070 KJ/Kg)	Thermal Efficiency of Engine (%)	Exhaust Energy (kW)
0.00559561	19.7	5.19	62092.5833	31.72681	13.02853
0.01458470	57.13	15.87	189866.916	30.08949	16.755883
0.02328622	89.3	23.72	283783.444	31.46765	17.937608
0.02997131	116.6	31.01	371000.194	31.42585	19.255962
0.03951476	147.4	44.74	535264.3889	27.537793	20.3122442
0.04586396	161.4	55.04	658492.444	24.51660	20.614267

7.4.2 Disc Style Thermoelectric Module Design

The cylindrical style thermoelectric module with a 50 mm inner diameter and 115 mm outer diameter is applied into the last design of the TE generator. As illustrated in Fig 7.25, the thermoelectric couples are placed between two ceramic surfaces by obtaining disc shape. One of the main obstacles in a half scale thermoelectric generator is misalignments among the TE modules, which cause gaps between the TE module surfaces and the heating plates. These gaps which occur due to an inequality in height, induce a significant power loss and therefore lower the efficiency of the system. This misalignment obstacle is overcome by decreasing the gaps between the heating plates and the cooling plates, however this method caused mechanical stress on the thermoelectric

calculations, design and simulation tools, the design process will test the following important performance characterisation:

- The theoretical maximum transmission power when the heat pipes are in use within the temperature ranges
- The heat pipe-heat exchanger design including the high-temperature heat pipes which withdraw heat from the exhaust pipe and cooling pipes which extract heat from the plates to the cooling water to determine the maximum amount of convective heat transfer theory.

7.4.3.1 Overall the hot end of the heat pipe heat transfer design calculations

The hot end of the heat pipe design calculations mainly involves the following key conditions:

1. The heat transmission power of a single high temperature heat pipe

Taking into account the temperature fluctuation range of the exhaust pipe, a copper and Dowtherm-A composite heat pipe, which has maximum 100W-150W range of heat transfer power is chosen.

2. The number of high-temperature heat pipes at a single TEG hot plate

The TEG single hot plate temperature is intended to be assembled in direct contact with the centre of the exhaust pipe with the heat pipes which provide a 6-axis radial divergence.

3. The arrangement of the heat pipe layers is designed to be placed with a 30° angle rotation between the previous and next layer under the consideration

of the heat pipe and vehicle exhaust convection heat transfer.

4. The design of a 40 layer TEG unit (80 TE module), which is shown in Fig. 7.26, contains 240 high temperature heat pipes which has heat transfer capabilities of 7.253kw to 30.421kw under different conditions of temperature and flow.

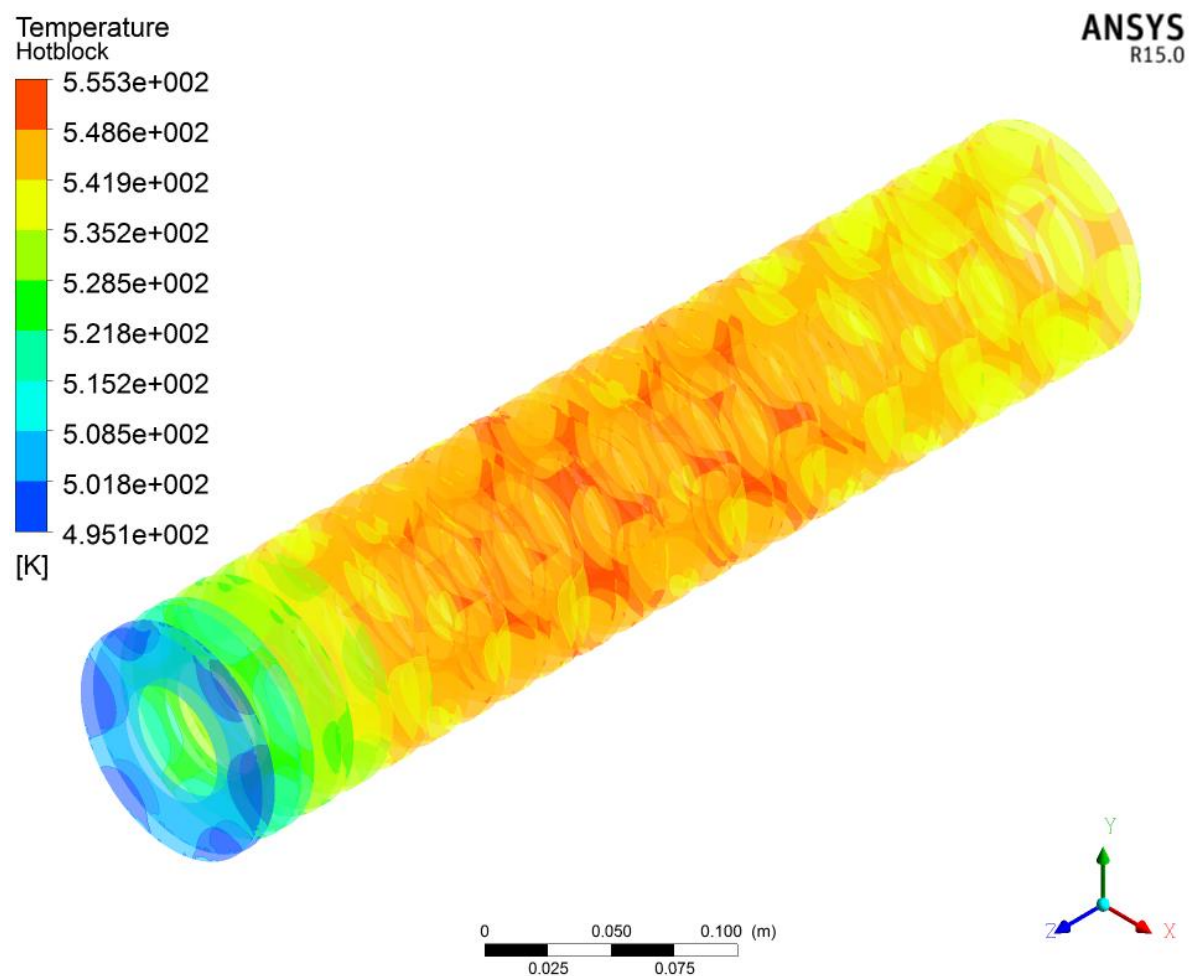


Figure 7-28 Metal hot plates temperature distribution.

Within the limitations of TEG efficiency, the TEG can produce more than 1kW of power generation when the supply of heat matches the maximum power

generation requirements. The TEG power generation will be calculated based on the actual TEG efficiency and limitations at specific conditions.

Table 7-12 Theoretical maximum heat transfer at each point of exhaust temperature status on TEG heat pipe heat exchanger design.

Exhaust gas temperature (K)	Density (kg/m ³)	Dynamic viscosity (10 ⁻⁵ N/s.m ²)	Mass flow rate (kg/s)	Reynolds Number
841.7	0.432	3.83191	0.011191231	8267.613171
986.7	0.380	4.23791	0.029169414	19484.69427
1031.7	0.364	4.36391	0.046572445	30211.40202
1089.8	0.343	4.52659	0.059942637	37487.14136
1119.4	0.332	4.60947	0.079029522	48535.10854
1133.1	0.327	4.64783	0.09172792	55868.74968

Table 7-13 Theoretical maximum heat transfer at each point of exhaust temperature status on TEG heat pipe heat exchanger design.

Nusselt Number	Convective heat transfer coefficient (W/m ² .K)	The total convective heat transfer high temperature heat pipe design (kW)
158.3183566	1629.467937	7.253
268.9186878	3164.236222	14.084

352.6435502	4310.720635	19.187
402.9485686	5163.665023	22.983
472.6862317	6199.579297	27.594
515.633059	6834.673227	30.417

7.4.3.2 TEG Mathematical Analysis

With the exhaust gas temperature at 1133.1K the calculation is demonstrated as following:

The exhaust gas with an inner diameter of 45mm and length of 500mm is examined due to the consideration of the thermoelectric power generation design and table 7.10 the Reynolds number is illustrated by:

$$\begin{aligned}
 Re &= \frac{\rho v D_h}{\mu} = \frac{m D_h}{\mu A} \\
 &= \frac{4 \times 0.09172792 \text{ kg/s} \times 0.045 \text{ m}}{4.64783 \times 10^{-5} \text{ N.s/m}^2 \times 3.14 \times 0.045^2 \times 10^{-6} \text{ m}^2} = 55868.74968
 \end{aligned} \tag{7-3}$$

According to the Reynolds number, the effective Nusselt number is calculated by:

$$\begin{aligned}
 Nu^*_{effective} &= CAF \times Nu_{theroy} \\
 &= CAF \times \frac{\left(\frac{f}{8}\right) \times Re \times Pr}{1.07 + 12.7 \times \sqrt{\left(\frac{f}{8}\right)} \times (Pr^{2/3} - 1)}
 \end{aligned} \tag{7-4}$$

where the inner Convective Augmentation Factors in the exhaust pipe CAF is 2.5, the Planck number Pr is 0.68. the Modified Fanning formula according to the Reynolds number is:

$$f = (0.79 \ln Re - 1.64)^{-2} = (0.79 \ln 55869 - 1.64)^{-2} = 0.020435592 \quad (7-5)$$

Then, the Nusselt number is:

$$Nu^*_{effective} = 2.5 \times \frac{\left(\frac{0.020435592}{8}\right) \times 55869 \times 0.68}{1.07 + 12.7 \times \sqrt{\left(\frac{0.020435592}{8}\right) \times (0.68^{2/3} - 1)}} = 515.6$$

Considering the number of layers, the correction coefficient provides the actual Nusselt number:

$$Nu_{total} = 1.05 \times Nu^*_{effective} = 541.38 \quad (7-6)$$

The convective heat transfer coefficient is illustrated by:

$$h = \frac{Nu_{total} \times \lambda}{D_h} = \frac{541.38 \times 0.0795295}{0.006(\text{heat pipe diameter})} = 7175.63 \text{ W/m}^2 \cdot K \quad (7-7)$$

where λ is the thermal conductivity of the exhaust gas temperature at 1133.1K. Based on the 25°C temperature variance in the high temperature heat pipe, the total heat transfer of hot side is calculated by:

$$\begin{aligned} Q_h &= N \cdot h \cdot A \cdot \Delta T = 240 \times 7175.63 \frac{\text{W}}{\text{m}^2} \cdot K \times 706.5 \times 10^{-6} \text{m}^2 \times 25K \\ &= 30416.5 \text{ W} = 30.4 \text{ kW} \end{aligned} \quad (7-8)$$

7.4.3.3 Overall the cold end of the heat pipe heat transfer design calculations

According to the radiator system of an automotive, the cooling water temperature operating range is 150 °C and below. The cooling water heat transfer and convection heat transfer is calculated to ensure the provision of sufficient cooling capacity. The cold end heat pipe temperature is assumed to be constant due to the physical parameters of the cooling water temperature, therefore the change is negligible and the heat transfer is calculated as follows:

Table 7-14 Cold end of the heat pipe design on convective heat transfer calculations.

The number of heat pipes at single layer	Velocity of flow (m/s)	Density (kg/m ³)	Dynamic viscosity (N/s.m ²)	Mass Flow (kg/s)	Reynolds Number
6	0.1	1000	0.000335	0.615126	4780

Table 7-15 Cold end of the heat pipe design on convective heat transfer calculations.

Planck number	Nusselt Number	Convective heat transfer coefficient (W/m ² .K)	Total convective heat transfer at high temp heat pipe (kW)	Heat transfer fin assembly design (kW)
2.095	48.72	5686.84	27.47	31.6

Cooling water flows through the cylindrical cooling unit which is shown in Fig. 7.29 within the inner diameter of 115mm, the outer diameter of 175mm and length of 500mm.

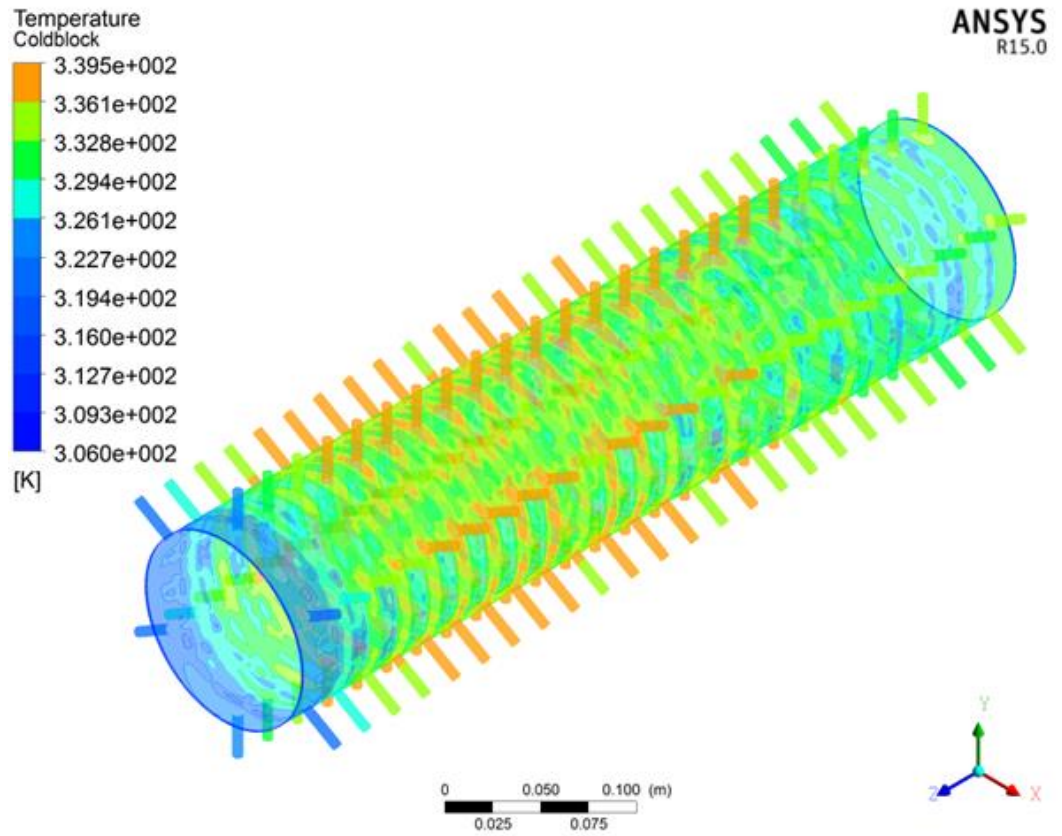


Figure 7-29 Metal cold plate temperature distribution.

The Reynolds number is calculated as follows:

$$Re = \frac{\rho v D_h}{\mu} = \frac{1000 \text{ kg/m}^3 \times 0.154 \text{ m/s} \times 0.0104 \text{ m}}{3.35 \times 10^{-4} \text{ N.s/m}^2} = 4780$$

where, v is the minimum cross-section of the flow rate and D_h is the minimum cross-section of the length. Corresponding to the Reynolds number, the Nusselt number is illustrated by:

$$Nu_{\text{effective}}^* = 0.193 Re^{0.618} Pr^{0.333} = 0.193 \times 4780^{0.618} \times 2.095^{0.333} = 46.4$$

The correction factor of 1.05 is due to the number of layers and the correction factor of 1.15 is due to the installed fins on the heat pipes. These are applied into the calculation to obtain the actual Nusselt number which is given by:

$$Nu_{total} = 1.05 \times 1.15 \times Nu_{effective} = 56$$

The convective heat transfer coefficient is illustrated by:

$$h = \frac{Nu_{total} \times \lambda}{D_h} = \frac{56 \times 0.609}{0.006(\text{heat pipe diameter})} = 5686.84 \text{ W/m}^2 \cdot \text{K}$$

According to the requirement of a 20° C temperature difference between the cooling water and the cold end of the heat pipe, the total heat transfer for 41 layers of cooling plate and 6 heat pipe at each layer is illustrated by:

$$Q_c = N \cdot h \cdot A \cdot \Delta T = 6 \times 41 \times 5686.84 \frac{\text{W}}{\text{m}^2} \cdot \text{K} \times 3.14 \times 0.006 \text{ m} \times 0.03 \text{ m} \times 20 \text{ K} = 15813.87 \text{ W} = 15.8 \text{ kW}$$

7.4.3.4 TEG generation design calculations

The sample parameters of a similar thermoelectric module that were provided by the manufacturer were adjusted to calculate the disc style thermoelectric module parameters. A single square 63.5 mm thermoelectric module has a maximum power output of 35 W and 5.7% efficiency when the required heat power, which is 606 W, is supplied. The required energy flux density for a square TE is:

$$q = \frac{Q_h}{A} = \frac{606 \text{ W}}{6.352 \text{ cm}^2} = 15.06 \text{ W/cm}^2 \quad (7-9)$$

The required heat energy for a single disc TEG is calculated by:

$$Q_{h_{disc}} = qA_{disc} = q \frac{\pi(D_{out}^2 - D_{in}^2)}{4}$$

$$= 15.06 \frac{3.14(11.5^2 - 5^2)}{4} = 1268 \text{ W} \quad (7-10)$$

Considering the actual number of TE couples in a square TE module to be half of the disc TE module, the power generating capacity of a single disc TEG is 70W with a 4V output voltage. Without considering the heat exchanger losses, the maximum theoretical power generation capacity of 80 ring TEGs and the required total heat transfer to produce maximum power is calculated by:

$$P_{total} = P_{single}N = 70\text{W}.80 = 5600\text{W} \quad (7-11)$$

$$Q_{h_{total}} = Q_{h_{single}} * N = 1268\text{W}.80 = 10.14\text{kW} \quad (7-12)$$

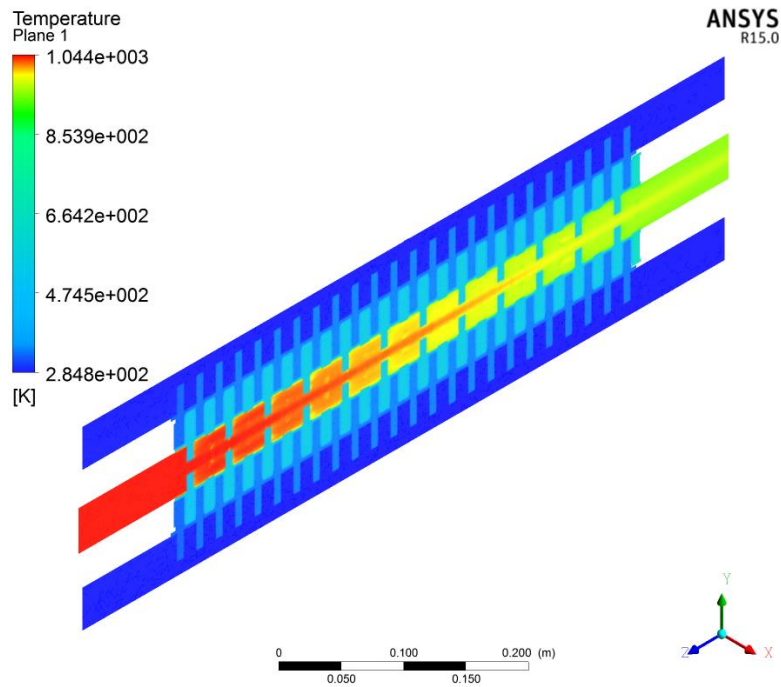


Figure 7-30 TEG system overall temperature distribution (symmetry plane).

Chapter 8 Conclusion

In this thesis, thermoelectric generation methodology is demonstrated with original work, innovative implementations, novel solutions, experimental studies, including testing and characterising the system performance of the thermoelectric generator unit, a simulation of the transient and dynamic TEG systems by applying converter and maximum power point tracking methods for TE generator implementations.

Chapter 3 initially demonstrated the topology of thermoelectric energy conversion theoretically. Secondly in light of the theoretical information about the TE, a novel transient heat transfer solution is introduced with an innovative 2-D heat transfer simulation. Lastly, a comparison between actual and simulation data is presented to fulfil the proof of accuracy.

In chapter 4, variant DC-DC converter topologies are described mathematically and electrically along with a statement of their advantages, disadvantages and capabilities. In addition to the DC-DC converter analysis, compatibility analysis for an automotive environment are taken into consideration as follows:

To adopt a converter system to future and current automotive systems, the H-Bridge DC-DC converter, which has both charge and discharge capability, is designed. Another main advantage of the H-Bridge DC-DC converter is the easy integration between a regenerative braking system and a thermoelectric power generator, so the size and cost can halve by using one converter instead of two.

Chapter 5 introduces dynamic response and mathematical analyses of a large scale thermoelectric power generator, which is implemented into a simulation program and real time simulation data is produced using an NEDC driving cycle. In addition to the dynamic response, the designed simulation program provides the power output and the required thermal input at a given initial temperature value to understand the system's response for specific temperature and heating powers.

Chapter 6 demonstrates the designed H-Bridge DC-DC converter which can provide a 48V at output. The reason for choosing this voltage level is to match the incremental power demand in an automotive, under the consideration of the future power level work of the automotive industry. A dead time management system for the H-Bridge, which is compulsory at full bridge applications to protect the MOSFETs, is also demonstrated in this chapter. In addition to the DC-DC conversion, P&O and incremental conductance MPPT methods are analysed and due to the design of converter, the H-Bridge converter is adopted to operate at P&O MPPT technic which is designed and presented algorithmically.

In conclusion, the test rig installations, designs and experimental measurements which are derived in the steady state and transient modes from actual TEGs are introduced in chapter 7 with the progress of an automotive TEG design.

Appendix A.

Table A.1: Large scale TEG simulation electrical output.

Pload(W)	Rin	Vo	Vload	Current
26.86464822	0.260563374	5.291481224	2.645740612	10.15392367
26.61011686	0.260426508	5.264970964	2.632485482	10.10836225
26.35338108	0.260284745	5.238084793	2.619042396	10.06222011
26.0945156	0.260138119	5.210826505	2.605413253	10.01549968
25.83359518	0.259986666	5.183199888	2.591599944	9.968203327
25.57069463	0.259830417	5.155208724	2.577604362	9.920333393
25.30588875	0.259669407	5.126856786	2.563428393	9.871892194
25.03925238	0.259503669	5.098147844	2.549073922	9.822882011
24.77086035	0.259333235	5.06908566	2.53454283	9.773305094
24.50078751	0.259158138	5.03967399	2.519836995	9.723163666
24.22910868	0.25897841	5.009916584	2.504958292	9.672459918
23.95589864	0.258794082	4.979817187	2.489908593	9.621196015
23.68123216	0.258605186	4.949379535	2.474689768	9.569374096
23.40518397	0.258411752	4.918607363	2.459303681	9.516996272
23.12782874	0.258213811	4.887504396	2.443752198	9.464064628
22.84924109	0.258011394	4.856074356	2.428037178	9.410581227
22.56949556	0.257804529	4.824320958	2.412160479	9.356548104
22.28866663	0.257593247	4.792247913	2.396123956	9.301967274
22.00682868	0.257377577	4.759858925	2.379929462	9.246840727

21.72405601	0.257157547	4.727157692	2.363578846	9.191170433
21.4404228	0.256933187	4.694147911	2.347073955	9.134958339
21.15600314	0.256704523	4.660833269	2.330416634	9.078206371
20.87087097	0.256471584	4.62721745	2.313608725	9.020916436
20.58510014	0.256234397	4.593304134	2.296652067	8.963090419
20.29876432	0.255992989	4.559096994	2.279548497	8.90473019
20.01193707	0.255747387	4.5245997	2.26229985	8.845837597
19.72469177	0.255497617	4.489815917	2.244907959	8.786414471
19.43710165	0.255243705	4.454749304	2.227374652	8.726462625
19.14923977	0.254985677	4.419403517	2.209701759	8.665983857
18.86117899	0.254723557	4.383782207	2.191891103	8.604979946
18.572992	0.254457372	4.34788902	2.17394451	8.543452657
18.28475128	0.254187145	4.311727598	2.155863799	8.481403738
17.99652912	0.2539129	4.27530158	2.13765079	8.418834922
17.70839758	0.253634662	4.2386146	2.1193073	8.355747929
17.4204285	0.253352453	4.201670287	2.100835143	8.292144462
17.13269349	0.253066298	4.164472267	2.082236133	8.228026213
16.84526391	0.252776218	4.127024162	2.063512081	8.163394858
16.55821089	0.252482237	4.089329591	2.044664795	8.098252061
16.27160529	0.252184376	4.051392167	2.025696083	8.032599473
15.98551771	0.251882657	4.013215502	2.006607751	7.966438732
861.0929811	10.27031275	187.6100085	93.80500423	365.0828594

Table A.2: Large scale TEG simulation thermal output

Qin_n	Qin_p	Qteg	Heat Flux
3.688982	5.872109812	683.4838145	15.13525312
3.660787	5.791918954	675.7526642	14.96405241
3.632512	5.712931721	668.1013666	14.79461997
3.604163	5.635123858	660.5284478	14.62692318
3.575741	5.558471448	653.0324533	14.46092982
3.547251	5.48295091	645.6119474	14.2966081
3.518695	5.408538998	638.2655139	14.13392666
3.490078	5.335212798	630.9917551	13.97285455
3.461401	5.262949723	623.7892923	13.81336124
3.432669	5.191727515	616.6567654	13.65541661
3.403883	5.121524238	609.5928325	13.49899094
3.375048	5.052318277	602.5961704	13.34405494
3.346166	4.984088337	595.6654738	13.19057969
3.31724	4.91681344	588.7994556	13.0385367
3.288272	4.850472921	581.9968465	12.88789786
3.259266	4.785046426	575.256395	12.73863545
3.230224	4.720513909	568.5768672	12.59072215
3.201149	4.656855634	561.9570468	12.44413103
3.172043	4.594052164	555.3957346	12.29883553
3.142909	4.532084366	548.8917488	12.15480949

3.113749	4.470933406	542.4439246	12.0120271
3.084565	4.410580746	536.051114	11.87046295
3.05536	4.351008141	529.712186	11.73009199
3.026137	4.292197639	523.426026	11.59088954
2.996897	4.234131575	517.1915361	11.45283128
2.967642	4.176792571	511.0076347	11.31589327
2.938375	4.120163534	504.8732563	11.18005191
2.909097	4.064227651	498.7873516	11.04528397
2.879811	4.008968388	492.7488872	10.91156656
2.850518	3.95436949	486.7568455	10.77887714
2.821221	3.900414972	480.8102247	10.64719354
2.791921	3.847089124	474.9080382	10.5164939
2.762619	3.794376502	469.0493151	10.38675673
2.733319	3.742261931	463.2330996	10.25796086
2.704021	3.6907305	457.458451	10.13008545
2.674726	3.639767557	451.7244436	10.00311002
2.645437	3.589358713	446.0301666	9.877014389
2.616156	3.539489833	440.3747237	9.751778711
2.586882	3.490147036	434.7572334	9.627383465
2.557619	3.441316695	429.1768285	9.503809446
125.0645	182.2240315	21975.46388	486.6307017

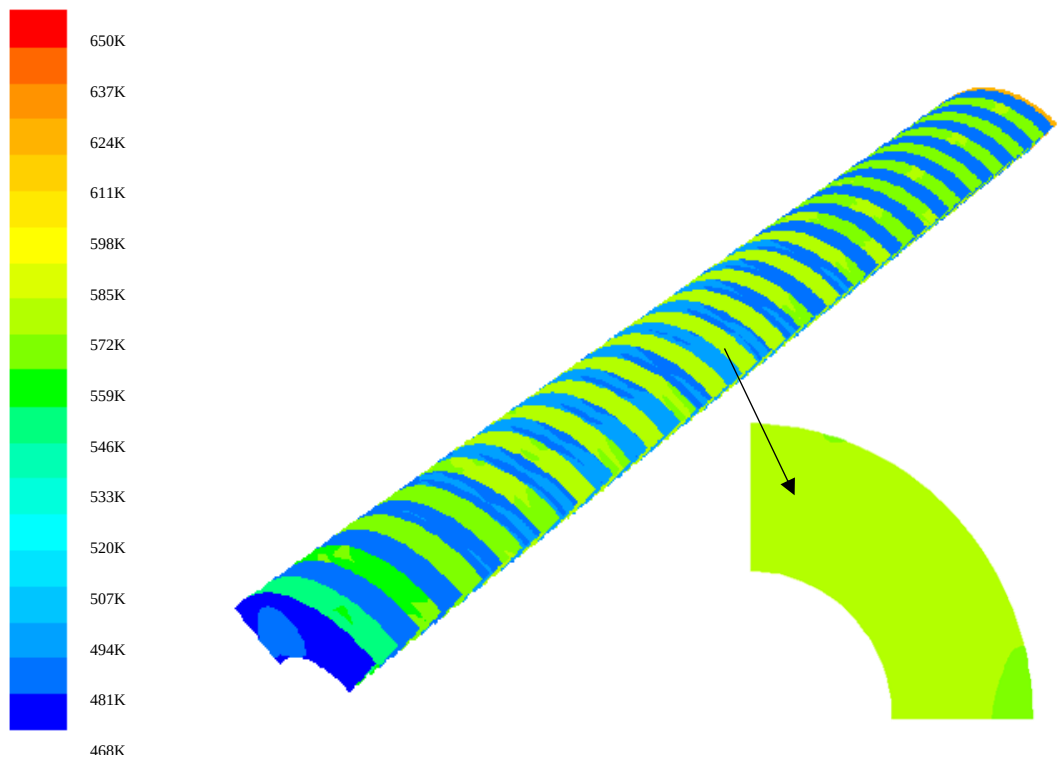


Figure A.1: Temperature contour of cell walls

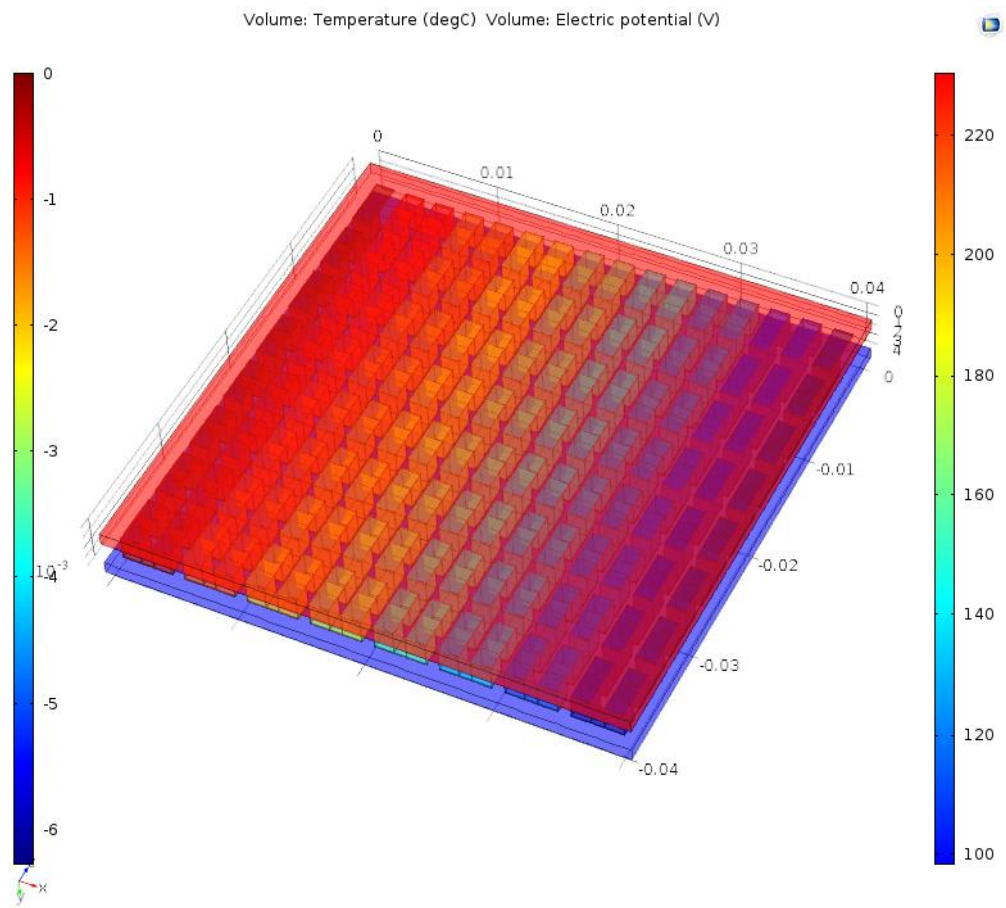


Figure A.2 ANSYS TE module design

Appendix B.

B.1.1 Temperature Values

%%% Initiates with this code

%%% Thot = 350C

tmp_pwr

dTblock=2;% temp difference between each block

dTpipe=400;%temp decrease between exhaust pipe and block (copper pipe)

for m=1:40

tmp_hot=350-(m-1)*dTblock;

tmp_cold=90;

hiz20_q

% DYNAMIC SIMULATION FOR NEDC DRIVING CYCLE

% th_pwr=fc_ex_th_pwr(l);

%

end

```
figure;  
  
subplot(5,1,1)  
  
plot(Pload)  
  
title('Pload')  
  
subplot(5,1,2)  
  
plot(Eo)  
  
title('Eo')  
  
subplot(5,1,3)  
  
plot(Vload)  
  
title('Vload')  
  
subplot(5,1,4)  
  
plot(Rin)  
  
title('Rin')  
  
subplot(5,1,5)  
  
plot(I)  
  
title('Current')
```

```
figure;

subplot(5,1,1)

plot(Qin_n)

title('Qin n')

subplot(5,1,2)

plot(Qin_p)

title('Qin p')

subplot(5,1,3)

plot(Q)

title('Qteg')

subplot(5,1,4)

plot(HeatFlux)

title('HeatFlux')

subplot(5,1,5)

plot(fc_ex_th_pwr)

title('th pwr')
```

```
Q1=0;
```

```
    for ml=1:40
```

```
        Q1=Q(ml)+Q1;
```

```
    end
```

```
    Qtotal=Q1;
```

```
Qtotal
```

```
%CYNAMIC SIMULATION FOR NEDC DRIVING CYCLE
```

```
% figure; plot(transpose(fc_ex_th_pwr)-Qtotal)
```

```
% for l=1:1185
```

```
% tmp_hot=fc_ex_gas_tmp(l)-400;
```

```
% tmp_cold=fc_clt_tmp(l);
```

```
%
```

```
% hiz20_q
```

```
% th_pwr=fc_ex_th_pwr(l);
```

```
% end
```

```
Pload1=0;
```

```
for ml=1:40
```

```
Pload1=Pload(ml)+Pload1;
```

```
end
```

```
Pload1
```

B.1.2. TE Thermal Power Calculations

format long

%%hiz20_q

hiz20_spec

hiz20_p

AbyL=side_1*side_2/leg_length;

I_n=Nocv/Rn/2;

I_p=Pocv/Rp/2;

Qlatt_n=Kn*dT*AbyL;

Qlatt_p=Kp*dT*AbyL;

Qsbck_hot_n=(Thot+273)*Sbck_avg_n*I_n;

Qsbck_hot_p=(Thot+273)*Sbck_avg_p*I_p;

Qjoule_n=I_n^2*Rn/2;

Qjoule_p=I_p^2*Rp/2;

$$Q_{in_n}(m) = Q_{latt_n} + Q_{sbck_hot_n} - Q_{joule_n};$$

$$Q_{in_p}(m) = Q_{latt_p} + Q_{sbck_hot_p} - Q_{joule_p};$$

$$width1 = Leg_no_side1 * side_1 + (Leg_no_side1 + 1) * eggwall_thick;$$

$$width2 = Leg_no_side2 * side_2 + (Leg_no_side2 + 1) * eggwall_thick;$$

$$Egg_area = (width1 * width2) - (Leg_no * area);$$

$$Q_{egg} = Therm_cond_egg * dT * Egg_area / Egg_length / 100;$$

$$Q(m) = Leg_no * (Q_{in_n}(m) + Q_{in_p}(m)) / 2 + Q_{egg};$$

$$width1 = side1_legno * side_1 + (side1_legno + 1) * eggwall_thick;$$

$$width2 = side2_legno * side_2 + (side2_legno + 1) * eggwall_thick;$$

$$HeatFlux(m) = Q(m) / (width1 * width2);$$

B.1.3 TE module electrical power calculations

```
format long
```

```
%%hiz20_spec
```

```
area=side_1*side_2;
```

```
segment_length=leg_length/segment;
```

```
segment_AL=area/segment_length;
```

```
segment_dT=dT/segment;
```

```
Tavg(1)=Tcold+(segment_dT/2)+273;
```

```
for j=2:segment
```

```
    Tavg(j)=Tavg(1)+(j-1)*segment_dT;
```

```
end
```

```
for i=1:segment
```

$$a_n(i) = a_coef1_n + a_coef2_n * Tavg(i) + a_coef3_n * (Tavg(i)^2) + a_coef4_n * (Tavg(i)^3) + a_coef5_n * (Tavg(i)^4);$$

$$a_p(i) = a_coef1_p + a_coef2_p * Tavg(i) + a_coef3_p * (Tavg(i)^2) + a_coef4_p * (Tavg(i)^3) + a_coef5_p * (Tavg(i)^4);$$

$$V_n(i) = a_n(i) * segment_dT;$$

$$V_p(i) = a_p(i) * segment_dT;$$

$$\rho_n(i) = \rho_coef1_n + \rho_coef2_n * Tavg(i) + \rho_coef3_n * (Tavg(i)^2) + \rho_coef4_n * (Tavg(i)^3) + \rho_coef5_n * (Tavg(i)^4);$$

$$\rho_p(i) = \rho_coef1_p + \rho_coef2_p * Tavg(i) + \rho_coef3_p * (Tavg(i)^2) + \rho_coef4_p * (Tavg(i)^3) + \rho_coef5_p * (Tavg(i)^4);$$

$$r_n(i) = \rho_n(i) / segment_AL;$$

$$r_p(i) = \rho_p(i) / segment_AL;$$

$$K_n(i) = (k_coef1_n + k_coef2_n * Tavg(i) + k_coef3_n * (Tavg(i)^2) + k_coef4_n * (Tavg(i)^3) + k_coef5_n * (Tavg(i)^4)) / 100;$$

$$K_p(i) = (k_coef1_p + k_coef2_p * Tavg(i) + k_coef3_p * (Tavg(i)^2) + k_coef4_p * (Tavg(i)^3) + k_coef5_p * (Tavg(i)^4)) / 100;$$

end

$S_{bck_avg_n} = \text{mean}(a_n);$

$S_{bck_avg_p} = \text{mean}(a_p);$

$N_{ocv} = \text{sum}(V_n);$

$P_{ocv} = \text{sum}(V_p);$

$R_n = \text{sum}(r_n);$

$R_p = \text{sum}(r_p);$

$K_n = \text{mean}(K_n);$

$K_p = \text{mean}(K_p);$

$\text{conn_length} = \text{eggwall_thick} + \text{side_1};$

$\text{conn_area} = \text{conn_width} * \text{conn_thick};$

$R_{\text{conn}} = \text{conn_res} * \text{conn_length} / \text{conn_area};$

$R_{\text{cont}} = 0;$

$E_o(m) = 0.83 * (\text{Leg_no} * (P_{ocv} - N_{ocv}) / 2);$

$V_{\text{load}}(m) = E_o(m) / 2;$

$R_{\text{in}}(m) = \text{Couple_no} * (R_p + R_n + R_{\text{conn}} + R_{\text{cont}});$

$$I(m)=V_{load}(m)/R_{in}(m);$$

$$P_{load}(m)=E_o(m)*E_o(m)/(4*R_{in}(m));$$

B.1.4. Specifications of TE module calculations

%%Specifications of the TE Module%%

format long

Thot=tmp_hot;

Tcold=tmp_cold;

dT=Thot-Tcold;

Leg_no=142;

Couple_no=71;

segment=20;

side_1=0.495;

side_2=0.495;

leg_length=0.267;

area=side_1*side_2;

side1_legno=12;

side2_legno=12;

conn_width=0.5;

conn_thick=0.15;

conn_res=100/38000000;

eggwall_thick=0.06;

Therm_cond_egg=0.1;

Egg_length=0.58;

Leg_no_side1=12;

Leg_no_side2=12;

%%%%%%%%Coefficiencies of Seebeck(alpha), resistivity (rho), Thermal
Conductivity(k)

a_coef1_n=7.4232215E-05;

a_coef2_n=-1.5018E-06;

a_coef3_n=2.9361E-09;

a_coef4_n=-2.499E-12;

a_coef5_n=1.361E-15;

a_coef1_p=-0.0002559037;

a_coef2_p=2.3184E-06;

a_coef3_p=-3.181E-09;

a_coef4_p=9.173E-13;

a_coef5_p=-4.88E-16;

rho_coef1_n=-0.00195922;

rho_coef2_n=1.791526E-05;

rho_coef3_n=-3.818E-08;

rho_coef4_n=4.9186E-11;

rho_coef5_n=-2.98E-14;

$\rho_coef1_p = -0.002849603;$

$\rho_coef2_p = 1.967684E-05;$

$\rho_coef3_p = -3.317E-08;$

$\rho_coef4_p = 3.4733E-11;$

$\rho_coef5_p = -1.90E-14;$

$k_coef1_n = 1.425785;$

$k_coef2_n = 0.006514882;$

$k_coef3_n = -0.00005162;$

$k_coef4_n = 1.1246E-07;$

$k_coef5_n = -7.60E-11;$

$k_coef1_p = 6.9245746;$

$k_coef2_p = -0.05118914;$

$k_coef3_p = 0.000199588;$

$k_coef4_p = -3.891E-07;$

$k_coef5_p = 3.0382E-10;$

B.2.1 Main Section

clear

clc

Simulation_Time=3000;

Number_Elements=20;

Num_high=20;

Num_low=20;

Q_inlet = 20 ; % heat flux input value in the thermal subcircuit

I = 0.00 ; % Current value in the electrical subcircuit

Re_total = 4.4 ; % Sum of electrical resistance values

Rth_total = 2 ; % Sum of thermal resistance values

T_amb = 323.15 ; % ambient temperature in the thermal subcircuit

R_high_total = 0.1 ; % thermal resistance of high side

R_low_total = 0.8 ; % thermal resistance of low side

Initial_Cond=zeros(2*Number_Elements+Num_high+Num_low+2,1);

%set up initial conditions for temperature

```

%for i=Num_high+Number_Elements+Num_low:-
1:Num_high+Number_Elements+1

%Initial_Cond(i)=T_amb+Q_inlet*R_low_total/(2*Num_low)+(Num_high+Number_Elements+Num_low-i)*Q_inlet*R_low_total/Num_low;

%end

%for i=Num_high+Number_Elements:-1:Num_high+1

%Initial_Cond(i)=Initial_Cond(Num_high+Number_Elements+1)+Q_inlet*(Rth_total/(2*Number_Elements)+R_low_total/(2*Num_low))+(Num_high+Number_Elements-i)*Q_inlet*Rth_total/Number_Elements;

%end

%for i=Num_high:-1:1

% Initial_Cond(i) = Initial_Cond ( Num_high + 1 ) + Q_inlet * ( Rth_total / ( 2
* Number_Elements) + R_high_total / ( 2 * Num_high )) + ( Num_high - i ) *
Q_inlet * R_high_total / Num_high;

%end

%set up initial conditions for voltage

%for

i=Num_high+Number_Elements+Num_low+1:Num_high+Number_Elements
+Num_low+Number_Elements

```

```

% Initial_Cond(i)=I*Re_total/Number_Elements;

%end

%Set up initial conditions for voltage boundary elements

%Initial_Cond(2*Number_Elements+Num_high+Num_low+1)=I*Re_total/Number_Elements;

%Initial_Cond(2*Number_Elements+Num_high+Num_low+2)=I*Re_total/Number_Elements;

%-----INITIAL CONDITIONS FOR TEST RUN-----
-----

%set up initial conditions for temperature

for i=Num_high+Number_Elements+Num_low:-1:1

Initial_Cond(i)=T_amb;

end

%set up initial conditions for voltage

for

i=Num_high+Number_Elements+Num_low+1:Num_high+Number_Elements
+Num_low+Number_Elements

Initial_Cond(i)=0;

```

end

%Set up initial conditions for voltage boundary elements

Initial_Cond(2*Number_Elements+Num_high+Num_low+1)=0;

Initial_Cond(2*Number_Elements+Num_high+Num_low+2)=0;

%-----

options=odeset('MaxStep', 1);

%, 'OutputFcn',@odeplot,'OutputSel', [1 2 3 4 5 6 7]

[tg,xg]=ode23(@thermoelectric1, [0 Simulation_Time], Initial_Cond, options,
Number_Elements, Q_inlet, T_amb, I, Re_total, Rth_total, Num_high,
Num_low, R_high_total, R_low_total);

x=xg.';

V= -sum (x (Num_high + Number_Elements + Num_low + 1:Num_high +
Number_Elements + Num_low + Number_Elements, size(x,2)));

% [0 Simulation_Time],Initial_Cond,options,

```

% thermoelectric2 (~, x, Number_Elements, Q_inlet, T_amb, I, Re_total,
Rth_total, Num_high, Num_low, R_high_total, R_low_total)

% [Tb,Tc]=thermoelectric2 (Number_Elements, Q_inlet, T_amb, I, Re_total,
Rth_total, Num_high, Num_low, R_high_total, R_low_total);

Vg=zeros(size(x,2),1);

for i=1:size(x,2)

Vg(i)=-

sum(x(Num_high+Number_Elements+Num_low+1:Num_high+Number_Elements+Num_low+Number_Elements,i));

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% for k = 1:100001

%   Tnm=x(1:60,k);

%   plot(Tnm)

%   axis equal

%   M(k) = getframe;

% end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

B.2.2 Thermoelectric 1

```
function [dx_dt] = thermoelectric1 (~, x, Number_Elements, Q_inlet, T_amb,  
I, Re_total, Rth_total, Num_high, Num_low, R_high_total, R_low_total)
```

```
Num = Number_Elements;
```

```
dx_dt = zeros (2 * Num + Num_high + Num_low + 2, 1);
```

```
alpha = zeros (Num, 1) ;
```

```
Relec = Re_total / Num;
```

```
Rther = Rth_total / Num;
```

```
Rhigh= R_high_total / Num_high;
```

```
Rlow= R_low_total / Num_low;
```

```
Chigh= 180 / Num_high; % heat capacity of high side
```

```
Clow= 40 / Num_low; % heat capacity of low side
```

```
Cther= 20 / Num; %heat capacity of thermal circuit
```

```
Celec= 500 e-5 * Num; % capacitance of electrical circuit
```

```
for i = 1 : Num % alpha becomes variable corresponding to temperature
```

```
alpha ( i ) = Sfun ( x ( Num_high + i ) );
```

```
end
```

```
% Sets up the place holder variables for temperature at boundary B and T at
boundary condition (instead of writing out this whole expression inside each of
the other expressions)
```

```
Tb = ( Rther * x (Num_high) + Rhigh * x ( Num_high + 1 ) + alpha (1) ^ 2 *
Rther * Rhigh * x ( Num_high + 1 ) ^ 2 / Relec – Rther * Rhigh * alpha (1) * x
(Num_high + 1 ) * x(Num_high + 2 * Num + Num_low + 1 ) / ( 2 * Relec )) / (
Rther + Rhigh + Rther * Rhigh * alpha(1) ^ 2 * x ( Num_high + 1 ) / Relec );
```

```
Tc = ( Rther * x ( Num_high + Num + 1 ) + Rlow * x ( Num_high + Num ) +
alpha(Num)^2 * Rther * Rlow * x ( Num_high + N ) ^ 2 / Relec + alpha(Num)
* Rther * Rlow * x(Num_high+Num) * x(Num_high + 2 * Num + Num_low +
2) / (2*Relec)) / (Rther + Rlow + alpha(Num) ^ 2 * Rther * Rlow * x
(Num_high + Num ) / Relec);
```

```
dx_dt ( 1 ) = ( Q_inlet + (x (2) - x(1)) / Rhigh ) / Chigh;
```

```
for i = 2 : Num_high - 1
```

```
dx_dt ( i ) = ( x ( i + 1 ) – 2 * x ( i ) + x ( i – 1 ) ) / Rhigh / Chigh ;
```

```
end
```

$$dx_dt (Num_high) = ((Tb - x (Num_high)) / (Rhigh / 2) - (x (Num_high) - x (Num_high-1)) / Rhigh) / Chigh;$$

$$\begin{aligned} dx_dt (Num_high + 1) = & ((1 / Relec) * (x (Num_high + Num + Num_low \\ & + 1) ^ 2 - alpha(1) * x (Num_high + Num + Num_low + 1) * ((x (Num_high \\ & + 2) + x (Num_high+1)) / 2 - Tb) / (1)) - alpha(1) * ((x (Num_high + 2) + x(\\ & Num_high + 1)) / 2 * (x (Num_high + Num + Num_low + 2) + x (Num_high \\ & + Num + Num_low + 1)) / 2 - Tb * x (2 * Num + Num_high + Num_low + 1 \\ &)) / Relec + (alpha (1) ^ 2 / Relec) * ((x (Num_high+2) + x(Num_high + 1)) \\ & * (x (Num_high + 2) - x (Num_high + 1)) / 2 - Tb * 2 * (x (Num_high + 1) \\ & - Tb)) + (x (Num_high + 2) - x (Num_high + 1)) / Rther + (Tb- x (\\ & Num_high + 1)) / (Rther / 2)) / Cther; \end{aligned}$$

$$\begin{aligned} dx_dt (Num_high + Num + Num_low + 1) = & (I - x(Num_high + Num + \\ & Num_low + 1) / Relec + alpha(1) * ((x (Num_high + 2) + x (Num_high + 1)) \\ & / 2 - Tb) / Relec) / Celec; \end{aligned}$$

for i = Num_high + 2 : Num_high + Num - 1

$$\begin{aligned} dx_dt(i) = & ((1 / Relec) * (x (Num + Num_low + i) ^ 2 - (1 / 2) * alpha(i- \\ & Num_high) * x(Num + Num_low+i)*(x(i+1) - x(i-1))) - alpha(i- \\ & Num_high)*((x(i+1)+x(i))/2*(x(Num+Num_low+i+1)+x(Num+Num_low+i)))/ \end{aligned}$$

$$2-(x(i)+x(i-1))/2*(x(Num+Num_low+i)+x(Num+Num_low+i-1))/2)/Relec \\ +(\alpha(i-Num_high)^2/Relec)*((x(i+1)+x(i)) * (x(i+1)-x(i))/2-(x(i)+x(i-1))*x(i)-x(i-1))/2)+ (x(i+1)-2*x(i)+x(i-1))/Rther)/Cther;$$

$$dx_dt (i + Num + Num_low) = (I - x (i + Num + Num_low) / Relec + \alpha (i - Num_high) * (x (i+1) - x (i-1)) / (2 * Relec)) / Celec;$$

end

$$dx_dt (Num_high + 2 * Num + Num_low) = (I - x (Num_high + 2 * Num + Num_low) / Relec + \alpha (Num) * (Tc - (x (Num_high + N) + x (Num_high + Num-1)) / 2) / Relec) / Celec;$$

$$dx_dt (Num_high + Num) = ((1/Relec) * (x (Num_high + 2 * Num + Num_low)^2 - \alpha(Num) * x (Num_high + 2 * Num + Num_low) * (Tc - (x(Num_high + Num) + x(Num_high + Num - 1)) / 2)) - \alpha (Num) * (Tc * x (2 * Num + Num_high + Num_low + 2) - (x (Num_high + Num - 1) + x(Num_high + Num)) / 2 * (x(Num_high + 2 * Num + Num_low) + x (Num_high + 2 * Num + Num_low -1)) / 2) / Relec + (\alpha(Num) ^ 2 / Relec) * (Tc * 2 * (Tc - x (Num_high+Num)) - (x(Num_high+Num)+x(Num_high+Num-1))*(x(Num_high+Num)-x(Num_high+Num-1))/2)+ (x(Num_high+Num-1)-x(Num_high+Num))/Rther + (Tc-x(Num_high+Num))/(Rther/2))/Cther;$$

$$dx_dt(Num_high+Num+1) = (-x(Num_high+Num+1) - Tc)/(Rlow/2) + (x(Num_high+Num+2) - x(Num_high+Num+1))/Rlow)/Clow;$$

```
for i = Num_high + Num + 2 : Num_high + Num + Num_low - 1
```

```
dx_dt(i) = ((x(i+1) - 2*x(i)+x(i-1)))/(Rlow))/Clow;
```

```
end
```

```
dx_dt ( Num_high + Num + Num_low ) = (( x ( Num_high + Num + Num_low  
- 1)- x(Num_high + Num + Num_low )) / (Rlow) + (T_amb - x(Num_high +  
Num + Num_low)) / ( Rlow / 2 )) / Clow;
```

```
dx_dt ( 2 * Num + Num_high + Num_low + 1 ) = ( I -2 * x(2*Num +  
Num_high + Num_low + 1) / Relec + 2 * alpha(1) * ( x ( Num_high +1 ) - Tb  
)/ Relec ) / ( Celec );
```

```
dx_dt ( 2 * Num + Num_high + Num_low + 2 ) = ( I - 2 * x ( 2 * Num +  
Num_high + Num_low + 2 ) / Relec + 2 * alpha (1) * ( Tc - x ( Num_high +  
Num )) / Relec ) / (Celec);
```

B.2.3 Thermoelectric 2

```
function [Tb,Tc]=thermoelectric2(~, x, Number_Elements, Q_inlet, T_amb, I,  
Re_total, Rther_total, Num_high, Num_low, R_high_total, R_low_total)
```

```
Num=Number_Elements;
```

```
dx_dt = zeros ( 2 * Num + Num_high + Num_low + 2 , 1);
```

```
alpha = zeros ( Num , 1 ) ;
```

```
Relec = Re_total / Num;
```

```
Rther = Rth_total / Num;
```

```
Rhigh = R_high_total / Num_high;
```

```
Rlow = R_low_total / Num_low;
```

```
Chigh = 180 / Num_high ; % heat capacity of high side
```

```
Clow = 40 / Num_low ; % heat capacity of low side
```

```
Cther = 20 / N ; % heat capacity of thermal circuit
```

```
Celec = 500 e-5 * N ; % capacitance of electrical circuit
```

for i = 1 : Num % alpha becomes variable corresponding to temperature.

alpha (i) = Sfun (x (Num_high + i));

end

%Sets up the place holder variables for T at boundary B and T at boundary
condition(instead of writing out this whole expression inside each of the other
expressions)

Tb = (Rther * x (Num_high) + Rhigh * x (Num_high + 1) + alpha (1) ^ 2 *
Rther * Rhigh * x (Num_high + 1) ^ 2 / Relec - Rther * Rhigh * alpha(1) *
x(Num_high+1) * x(Num_high+2 * Num + Num_low + 1) / (2 * Relec)) / (
Rther + Rhigh + Rther * Rhigh * alpha(1) ^ 2 * x (Num_high + 1) / Relec);

Tc = (Rther * x (Num_high + N + 1) + Rlow * x (Num_high + Num) +
alpha (Num) ^ 2 *Rther * Rlow * x (Num_high + Num) ^ 2 / Relec +
alpha(Num) * Rther * Rlow * x(Num_high+Num) * x (Num_high + 2 * Num
+ Num_low + 2) / (2 * Relec)) / (Rther + Rlow + alpha(Num) ^ 2 * Rther *
Rlow * x (Num_high + Num) / Relec);

dx_dt (1) = (Q_inlet + (x (2) - x (1)) / Rhigh) / Chigh;

for i = 2 : Num_high - 1

$$dx_dt(i) = (x(i+1) - 2 * x(i) + x(i-1)) / Rhigh / Chigh;$$

end

$$dx_dt(Num_high) = ((Tb - x(Num_high)) / (Rhigh / 2) - (x(Num_high) - x(Num_high - 1)) / Rhigh) / Chigh;$$

$$\begin{aligned} dx_dt(Num_high + 1) = & ((1 / Relec) * (x(Num_high + Num + Num_low + 1) ^ 2 - \alpha(1) * x(Num_high + Num + Num_low + 1) * ((x(Num_high + 2) + x(Num_high + 1)) / 2 - Tb) / (1)) - \alpha(1) * ((x(Num_high + 2) + x(Num_high + 1)) / 2 * (x(Num_high + Num + Num_low + 2) + x(Num_high + Num + Num_low + 1)) / 2 - Tb * x(2 * Num + Num_high + Num_low + 1)) / Relec + (\alpha(1) ^ 2 / Relec) * ((x(Num_high + 2) + x(Num_high + 1)) * (x(Num_high + 2) - x(Num_high + 1)) / 2 - Tb * 2 * (x(Num_high + 1) - Tb)) + (x(Num_high + 2) - x(Num_high + 1)) / Rther + (Tb - x(Num_high + 1)) / (Rther / 2)) / Cther; \end{aligned}$$

$$dx_dt(Num_high + Num + Num_low + 1) = (1 - x(Num_high + Num + Num_low + 1) / Relec + \alpha(1) * ((x(Num_high + 2) + x(Num_high + 1)) / 2 - Tb) / Relec) / Celec;$$

for i = Num_high + 2 : Num_high + Num - 1

$$dx_dt(i) = ((1 / Relec) * (x(Num + Num_low + i) ^ 2 - (1 / 2) * \alpha(i - Num_high) * x(Num + Num_low + i) * (x(i + 1) - x(i - 1))) - \alpha(i$$

$$\begin{aligned}
& -\text{Num_high}) * ((x(i+1) + x(i)) / 2 * (x(\text{Num} + \text{Num_low} + i + 1) + x(\text{Num} \\
& + \text{Num_low} + i)) / 2 - (x(i) + x(i-1)) / 2 * (x(\text{Num} + \text{Num_low} + i) + x(\text{Num} \\
& + \text{Num_low} + i - 1)) / 2) / \text{Relec} + (\alpha(i - \text{Num_high})^2 / \text{Relec}) * \\
& ((x(i+1) + x(i)) * (x(i+1) - x(i)) / 2 - (x(i) + x(i-1)) * (x(i) - x(i-1)) / 2) + \\
& (x(i+1) - 2 * x(i) + x(i-1)) / \text{Rther}) / \text{Cther};
\end{aligned}$$

$$\begin{aligned}
& dx_dt(i + \text{Num} + \text{Num_low}) = (I - x(i + \text{Num} + \text{Num_low}) / \text{Relec} + \alpha \\
& (i - \text{Num_high}) * (x(i + 1) - x(i - 1)) / (2 * \text{Relec})) / \text{Celec};
\end{aligned}$$

end

$$\begin{aligned}
& dx_dt(\text{Num_high} + 2 * \text{Num} + \text{Num_low}) = (I - x(\text{Num_high} + 2 * \text{Num} + \\
& \text{Num_low}) / \text{Relec} + \alpha(\text{Num}) * (Tc - (x(\text{Num_high} + \text{Num}) + x(\text{Num_high} + \text{Num} - 1)) / 2) / \text{Relec}) / \text{Celec};
\end{aligned}$$

$$\begin{aligned}
& dx_dt(\text{Num_high} + \text{Num}) = ((1 / \text{Relec}) * (x(\text{Num_high} + 2 * \text{Num} + \\
& \text{Num_low})^2 - \alpha(\text{Num}) * x(\text{Num_high} + 2 * \text{Num} + \text{Num_low}) * (Tc - \\
& (x(\text{Num_high} + \text{Num}) + x(\text{Num_high} + \text{Num} - 1)) / 2)) - \alpha(\text{Num}) * (\\
& Tc * x(2 * \text{Num} + \text{Num_high} + \text{Num_low} + 2) - (x(\text{Num_high} + \text{Num} - 1) + x \\
& (\text{Num_high} + \text{Num})) / 2 * (x(\text{Num_high} + 2 * \text{Num} + \text{Num_low}) + x(\text{Num_high} + 2 * \text{Num} + \text{Num_low} - 1)) / 2) / \text{Relec} + (\alpha(\text{Num})^2 / \text{Relec}) \\
& * (Tc^2 * (Tc - x(\text{Num_high} + \text{Num})) - (x(\text{Num_high} + \text{Num}) + x(\text{Num_high} + \text{Num} - 1)) * (x(\text{Num_high} + \text{Num}) - x(\text{Num_high} + \text{Num} - 1)) / 2) + (x(\text{Num_high} + \text{Num} - 1) - x(\text{Num_high} + \text{Num})) / \text{Rther} + (Tc - x(\text{Num_high} + \text{Num})) / (\text{Rther} / 2)) / \text{Cther};
\end{aligned}$$

```

dx_dt ( Num_high + Num + 1 ) = ( - ( x ( Num_high + Num + 1 ) - Tc ) / (
Rlow / 2 ) + ( x(Num_high + Num + 2 ) - x ( Num_high + Num + 1 ) ) / Rlow )
/ Clow;

```

```

for i = Num_high + Num + 2 : Num_high + Num + Num_low - 1

```

```

dx_dt(i) = ((x(i+1) - 2*x(i)+x(i-1)))/(Rlow))/Clow;

```

```

end

```

```

dx_dt ( Num_high + Num + Num_low ) = (( x ( Num_high + Num + Num_low
- 1 ) - x(Num_high + Num + Num_low ) ) / ( Rlow ) + ( T_amb - x (
Num_high + Num + Num_low ) ) / ( Rlow / 2 ) ) / Clow;

```

```

dx_dt ( 2 * Num + Num_high + Num_low + 1 ) = ( I - 2 * x ( 2 * Num +
Num_high + Num_low + 1 ) / Relec + 2 * alpha (1) * ( x ( Num_high + 1 ) - Tb
) / Relec ) / ( Celec );

```

```

dx_dt ( 2 * Num + Num_high + Num_low + 2 ) = ( I - 2 * x(2*Num +
Num_high + Num_low + 2 ) / Relec + 2 * alpha (1) * ( Tc - x ( Num_high +
Num ) ) / Relec ) / ( Celec );

```

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