Compact Micro scale Multi- Source (Solar and Thermal) Energy harvesting IC with regulated Multi load Power Management scheme.

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Department of Electrical Engineering

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Declaration

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Approval Sheet

This thesis entitled **Compact micro scale Multi-source (Solar and Thermal) Energy harvesting IC with regulated multi load Power management scheme** by **Annam Abhilash** is approved for the degree of Master of Technology from IIT Hyderabad.

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Dedication

To my family, my teachers & friends

Abstract

Power is required for all man-made systems to work and perform their corresponding activi-ties.Generation of power in large scale is carried out from power grids and supplied to systems that need high power whereas systems requiring less power are supplied from batteries. Batteries need to be replaced after their lifetime which seem to be a less attractive option in applications where systems are placed out of reach for humans as WSN nodes or in some of biomedical systems which are kept inside human body. The need for a self-supporting system i.e. a system that produces energy by itself and supports all the modules by powering them by itself is increased. A harvesting system that harvests energy from the ambience and converting that energy into electrical form and supplying the power to loads or storing in a battery is the solution for all the problems mentioned above. Solar, thermal, vibration and RF are the sources in the ambience from which energy can be harvested and supplied to load or charged into a battery. Availability of a single energy source(thermal,vibration,solar,RF) at all instances cannot be guaranteed creating a situation of insufficient supply of power to loads or unable to charge the load capacitor to the required voltage. Usage of multiple sources for harvesting energy is a prominent solution to the above mentioned problem. Designing a microscale energy harvesting from multiple sources is the main motto behind the current work.TEG and piezo are compatible to be used alternatively in the system because of their close resemblance in their energy densities. Therefore TEG and piezo have been used as two input sources for the system. The other modules in the system include design of a buck boost power converter that switches between buck and boost modes depending on the source connected to the system and the input voltage available at the input. The other module being a digital controller that generates clocks for power switches, signals that decide if TEG or PV need to be connected to the system.Intra source selection block for TEG array where multiple TEG sources switch between series or parallel depending on the voltage available across each TEG source so as to increase the net power from the TEG. The load is a capacitor that needs to be charged to 1.8V where the system stops working once the capacitor gets charged to the desired voltage. Idea of sharing a single inductor between two different sources without using two power converters for individual sources is implemented. Using the dead time of inductor current of TEG for PV source is the main thought behind the development of the current system. System is designed considering all the specifications, constraints, functionality

has been verified and the simulation results are included. Scope for the improvement of the system design in various modules have been described at the end of the thesis.

Contents

Chapter 1

Introduction

1.1 Energy Harvesting

All systems need power to work and perform the prescribed activities. Continuous supply of power to any system using cables is not feasible all times and hence mode of supplying power is changed to using batteries and capacitor banks. Electrical and mechanical systems are powered using huge batteries where as electronic systems does not require large voltages to work and hence smaller batteries or super capacitors suffice the need. Batteries drain power in their life time and replacing them involves huge efforts especially in the systems that are not accessible easily such as wireless sensors. Modern smart city and IoT applications have adopted self powering scheme eliminating the use of external batteries or frequent battery replacement. Harvesting energy from renewable energy sources available in the ambiance as such solar, thermal, vibration and RF has gained importance in the recent years. Inconsistent input power, availability of low power at the input side, extracting maximum power from the input transducer, kick start the harvester system, minimizing power usage of the sub blocks in the system are the challenges involved in developing an energy harvester system. Maximum power extraction from the source is an essential part of any energy harvesting system due to the extremely low power available from the source.

As solar energy is most abundant in the ambience, harvesting energy from it seems to be a promising solution. Thermo electric generators (TEG) have high energy densities and are also consistent when compared to other energy sources. Piezo-electric source on the other hand also have comparable energy densities to TEG ranging from 10 to several hundreds of uW/cm3. Due to the very low power available from the RF sources, design of interface circuits to scavenge energy from RF is very challenging. The availability of the renewable sources in the ambience is shown in Figure 1.1

1.2 Hybrid energy Harvesting

A system that is being powered from a single energy source need to work in conditions where the availability of the source meets the design specifications of the energy harvester system. The unavailability of the source makes the system either to shut down or to go into sleep state depending

Energy Source	Performance
Ambient Light	Indoor 10uW/cm² (low illumination) Typical Office 100uw/cm² Outdoor 10mW/cm² Full bright sun 10mw/cm²
Vibrational	4uW/cm³ (human motion Hz range) 800 uW/cm³ (machines k-Hz range) These numbers depend heavily on size excitations, technologies, etc. Typically: Piezoelectric ~ 200uW/cm³ Electrostatic ~ 50-100uW/cm³ Electromagnetic < 1uW/cm³
RF	RFID 100uW/cm² GSM 4uW/cm² WiFi 1uW/cm² These numbers depend heavily on frequency of operation and distance between base station and receiver
Temperature Difference	Human 25uW/cm2-60uW/cm² Industry 10mW/cm²

Figure 1.1: Various sources and their energy densities

on the design. A hybrid system with different input sources solves the above mentioned problem by working in wide input conditions where the unavailability of a single source doesn’t make the system dysfunctional but works with other input sources. The choice of input sources depends on the system speci cation and the ambience where the system has been proposed to be placed. Each source in turn has the ability to have an array of sources to increase the net power delivered by the source by increasing the open circuit voltage or closed circuit current.

The need for the hybrid harvesting system also arises when the power requirement of the sub-systems in the chip increases where single intermittent energy source cannot handle the unpredictable transient power requirement of the system, which clearly enforces the usage of more than one source of energy. A hybrid system is always preferred owing to its compact nature and reusability of controls and hardware, for driving such loads operating at different supply voltages with dynamic power profile with respect to the system operation. A robust MIMO system, powered by a hybrid energy harvesting array of heterogeneous energy transducers for multi supply driving, using single inductor based architecture by analysing all possible trade-offs and feasibilities is the design needed.

1.3 Objective of work

Self powered multi-mode hybrid energy harvesting system that supply power to loads is designed according to the speci cations of loads, input source. Design is also done depending on the switching logic of the power converter. Load for the designed system is a capacitor of 10uH that will be charged to a voltage of 1.8V.Inductor sharing methodology in converter design is the key aspect in the design of the hybrid energy harvesting system. Detailed research of the input sources, power converter and methodology for the design of the hybrid system is carried out and the hybrid system has been designed.

1.4 Literature review

Research is being going on the design of an energy harvesting system that harvests energy from the energy sources in the ambience. Research in the field of hybrid energy harvesting both in micro level and macro level of powers due to its many advantages over single sourced energy harvesting system has increased in recent times. The below mentioned table gives an overview of different works carried out for the design of hybrid system.

As can be seen from the table, [8] is a hybrid energy harvesting system having photovoltaic, thermal, vibration as input sources. It is a microscale energy harvesting system with a peak efficiency of 83% while converter being a buck-boost converter that performs MPPT on all the input sources. [10] is a hybrid system that is made from discrete board with thermal and solar being the inputs for the system. [9] is a hybrid system with thermal and piezo sources as inputs that has a rectifier and LDO as a converter. Brief details about the other works can be understood from the table.

Description of the work is explained chapter wise in the thesis. Second chapter gives a detailed description of all modules in the designed multi source multi-mode hybrid energy harvesting system. Third chapter has the simulation results and the thesis is concluded by briefing about the future works that need to be done to improve the system.

Reference	**8**	**10**	**9**	**11**	**1**
inputs	Photovoltaic, thermal, vibration	Thermal, solar	Thermal , piezo	Thermal,vibration ,RF,solar	Photovoltaic, battery
input range	20mV-0.16V: thermal 0.15-0.75V : solar 1.5-5V : piezo	380lux – 1010lux: solar 5K-10K-temp diff: thermal	4v-(-2v) : thermal	0.7-5V	0-40uW(0-4.8V)- PV cell 130uAH-battery
Peak efficiency	83%	94%	66%	89.6%	93%
MPP	yes	yes	no	yes	yes
Technology node	0.35um	Using discrete board	0.8um smart power SOI	0.35um-BCD	0.5um
Power converter	Buck-boost	boost	Rectifier+LDO	Buck-boost	Buck-boost
Power consumption	NA	135uW	NA	NA	15mW
year	*Ieee journal of solid-state circuits* -2012	Transactions on industrial electronics-2011	Transactions on power electrnics-2015	Transactions on power electrnics-2015	*ISSCC*-2015

Figure 1.2: Literature review of hybrid energy harvesting systems

Chapter 2

System Architecture and Review

2.1 Hybrid energy harvesting System

Due to the unavailability of an energy source at all time instances, a system with more than one input source is an attracting solution. Using different power converter modules to transfer power from sources to loads is not an option to go with due to increased number of components like switches, inductors. To reduce their number, components can be shared among all the sources by generating signals for the switches corresponding to the source that uses them. In short only a single source uses the converter module at a time where the other sources will be in idle state at that time. An energy harvesting system has many modules which work in correlation with each other till the output is supplied with the required power and then goes into hibernate mode depending on the design. Input transducer, MPP tracking, Convertor, digital controller, battery management, regulator, loads form the main parts of harvester system.

Overview and design challenges of the hybrid energy harvesting system to be designed can be understood from Figure 2.1 and table 2.1.Each module need to be designed with utmost care so as to get high efficiency and low power consumption. A brief description of each module is given in the following paragraph and an in depth explanation about each module forms the remaining part of the chapter.

Maximum power point tracking (MPPT) need to be done to extract maximum power from the transducer. There are many ways to perform MPPT such as hill climbing, perturb and observe, fractional open circuit voltage method etc. and one of it is chosen depending on the source from which maximum power need to be extracted as the characteristics of each source are different. Converter can be charge pump (inductor-less) or inductor based and it is chosen based on the efficiency required. Digital controller is used to perform the specified logic and give the output signals accordingly. Loads are decided based on the requirement and the examples are WSN nodes which need to power to operate, super capacitors which can store charge. Battery management module is required when an external battery in which charge is being dumped into it when it is used along with other loads. Battery management block prevents battery voltage to fall below its under threshold voltage or go above its over threshold voltage. More than one transducer need to be connected at the input side for a hybrid energy harvesting system. There are many ways of connecting the inputs to the converter such as time division multiplexing [7], priority based etc. from which a method is chosen based on many factors such as availability of input, power requirement etc. The work done mainly focuses on the design of a hybrid energy harvesting system using TEG and Solar as input sources.

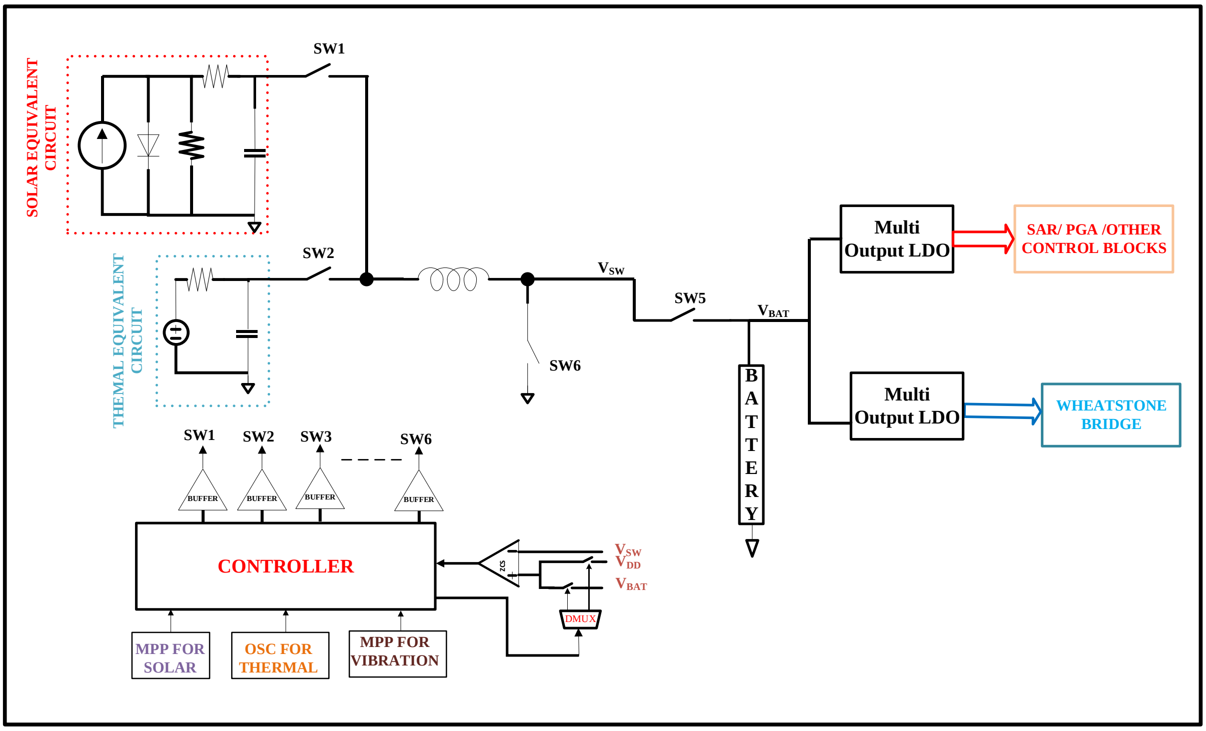


Figure 2.1: Architecture of the designed hybrid energy harvesting system

2.2 System Architecture

In depth understanding about the types of energy sources available in the nature, ways to extract maximum power from each source because each source has diff- erent power characteristics is important in the design of an energy harvesting system. Detailed description of each module in an energy harvesting system is given below.

2.2.1 Input sources selection

As mentioned earlier there are sources such as solar, TEG, vibration, RF in the ambience from which energy can be harvested. Each source has different characteristics such as output voltage form, energy density, output resistance etc. The below mentioned table specifies the form of output voltage for energy sources available in the ambience.

Design challenges	Issues	Proposed solutions
Multi source selection	**TEG Cell & PV Cell**	**1. Controller for switching into series/parallel mode based on input power availibility**
Simultaneous MPPT for TEG & piezo	**1. Different MPP mechanisms** **2. Different switching frequencies for MPP** **3. Single converter to be shared by all sources**	**1. FOCV method has been used for PV source** **2. Fixed frequency mode for TEG** **3. Time-multiplexed converter sharing**
Power converter design	**1. Shared Inductor** **2. Frequency selection**	**1. Optimal inductor value based on peak current and switching frequency** **2. Digital controller has been designed to generate clock signals**

Figure 2.2: Overview of design challenges and proposed solutions

Table 2.1: Energy sources and their output voltage form

Energy source	**Output voltage Type**
Solar	DC
TEG	DC
Piezo	AC
RF	AC

As a DC source can be directly connected to the converter, rectification is not required for solar and TEG inputs where as in the case of piezo and RF rectification need to be done from AC-DC before connecting it to the converter. IN spite of abundant availability of the RF energy in the ambience, its lesser power density makes it a less preferred input source for the hybrid system where as solar energy due to its high density is not compatible to use with TEG and piezo sources. Therefore the system is finalized to be sourced with TEG and piezo as input sources in main converter mode and hybrid start-up of RF and solar as startup. TEG is connected directly whereas piezo is rectified using a rectifier before connecting to the converter. As individual source has less input power they can be in turn arranged in array format so as to increase the input power. Approximate energy densities of sources can be seen from the below table.

Table 2.2: Sources and their corresponding energy densities

Source	**Harvested power**
Solar-Ambient-Indoor	10 uW/cm2
Solar-Ambient-Outdoor	10 mW/cm2
Vibration- Human	4uW/cm2
Vibration- Industrial	100uW/cm2
Thermal-Human	30uW/cm2
Thermal-Industrial	10mW/cm2
RF-Cell phone	0.1uW/cm2

THERMO ELECTRIC CONVERSION is the conversion of thermal energy into electrical energy or vice-versa according to Peltier or Seebeck effect. Seebeck effect is the generation of electricity from the heat ow through the material whereas the reverse being the Peltier effect. No generation of excessive waste during energy conversion due to direct conversion, ability to make efficient use of exhaust heat, maintenance free due to no provision of movable parts such as a motor and a turbine, and so on are the characteristics of thermal electric conversion and thus attracts attention as a technique for high-e ciency use of energy. A thermo electric generator has two plates (electrodes) across which voltage is generated by the heat ow through the material. It can be electrically characterized as a voltage source (with voltage equal to open circuit voltage of TEG) in series with a resistance (internal impedance of TEG).As described above the electrical voltage generated between the two plates is directly proportional to the temperature difference across them so the voltage increases with an increase in the temperature. The internal resistance of the voltage source increase with the temperature due to its positive temperature coefficient.

The voltage of a single TEG transducer ranges from tens of millivolts to hundreds of millivolts depending on the temperature difference between the two plates and the internal resistance will be in ohms for each transducer. So as to increase the voltage or current, a transducer array can be made by connecting many single transducers together each having same or di erent voltages and can be connected in any manner so as to attain the required voltages and current values. In an array, when transducers are connected in series there will be a net increase in the voltage whereas there will be an increase in current when they are connected in parallel. Due to mA current owing through a single transducer there will be a huge voltage drop due to the internal resistance of a TEG transducer directly effecting the power efficiency that can be achieved. There are many energy harvesting systems designed with TEG as input source [3].

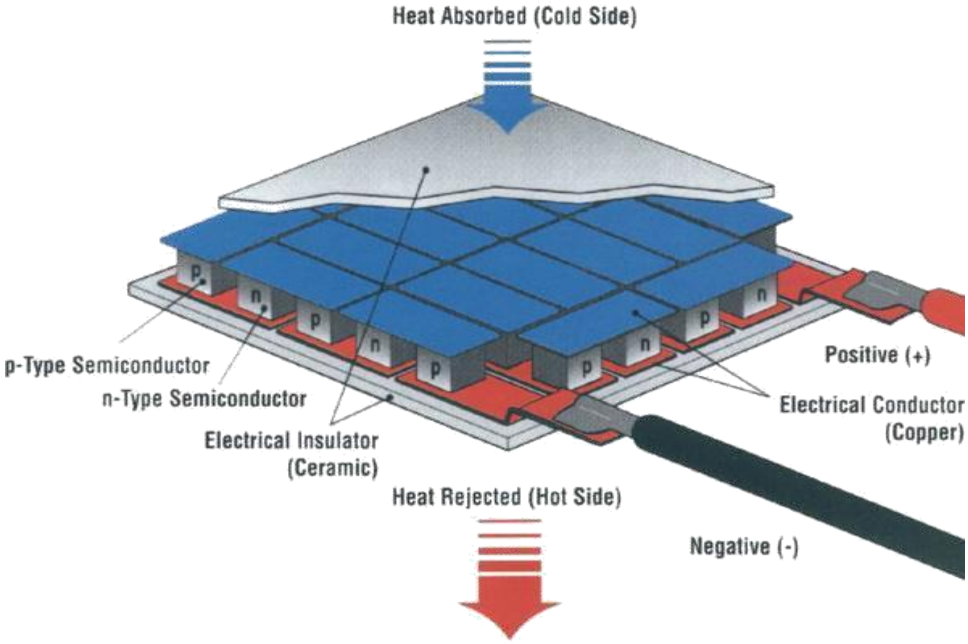
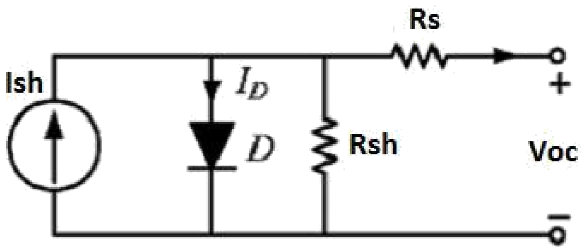


Figure 2.3: TEG transducer

One analog comparator compares the voltage across a single transducer with 5mV reference and gives a HIGH output when the voltage is above the threshold indicating that the TEG power is sufficient to power the system. If the output of the comparator is LOW the low signals that will be going as an input to the other stage makes TEG to get disconnected from the converter concluding that the TEG will be acting as a source to the system only if the TEG power is sufficiently high. The other comparator compares the voltage of a single source with the second reference.

Initially the modeling of **solar cell** is done with the discrete components as shown in Fig. below. The corresponding values of V_{oc}, V_{mpp} , I_{sh}, I_{mpp} of this solar cell model is given in Fig This solar cell model is used for performing simulation and verifying the system modeling as shown in section. Since this model works ne only for particular temperature and irradiance, we seek an for alternative solution to cater irradiance change and temperature variation for more accurate results. For matching with real world scenarios, a real solar cell data sheet is taken. Using equations fromand parameter values given in the datasheet solar cell model is done in verilog A. This model accounts for both irradiance and temperature e ects. The simulation plot closely matches with the datasheets plots. Simulation plot is discussed in section.

For implementing MPPT FOCV technique is used, which will be discussed in detail in section. To model the same a DC source of 329mV (equivalent to V_{mpp} of solar cell) is used as reference for MPP. For comparison of V_{solar} with this reference voltage V_{mpp} an interface circuit i.e. ideal comparator is implemented in Verilog-A coding. Depending on the decision of this comparator, solar cell will be connected / disconnected to the charger through switch SW2, so that it is regulated to V_{mpp} reference ensuring MPPT operation. Simulation results shown in section will validate the same.



Param	Value
Voc	439mV
Isc	15mA
Vmpp	329mV
Impp	12.8mA
Rs	1.3K
Rsh	100u
Is	6e-10

Figure 2.4: Model of solar cell with discrete component.

Table 2.3: Value of components used in implementation of ideal boost converter.

Component	Value
Inductor	40uH
Capacitor (V_{cap})	4.7uF
Duty ratio (Vclk!)	90.01
Clock frequency (Vclk!)	1MHz

To step up the voltage from V_{mpp} to 1.8 Volt an ideal boost converter with ideal inductor and switch is implemented. To drive the switch of ideal boost converter an ideal clock is used whose duty ratio is adjusted such that the input voltage is boosted from 329mV to more than 1.8 V. The corresponding values of components used in charger are given below in Table

Battery management block is modeled with three ideal comparators (Verilog A) for undervoltage and overvoltage protection and batter ok signal generation. The functionality of each is explained in section in detail. To model constant voltage reference (BGR), a dc source of 1.25V is used. V_{cap} voltage is scaled down through resistor divider as shown in Fig above. For over voltage V_{cap} is directly compared with Dc source (ov thr) of value 1.8 Volt. In this way all the signals are generated to control the system operation. The threshold voltages for all region are given.

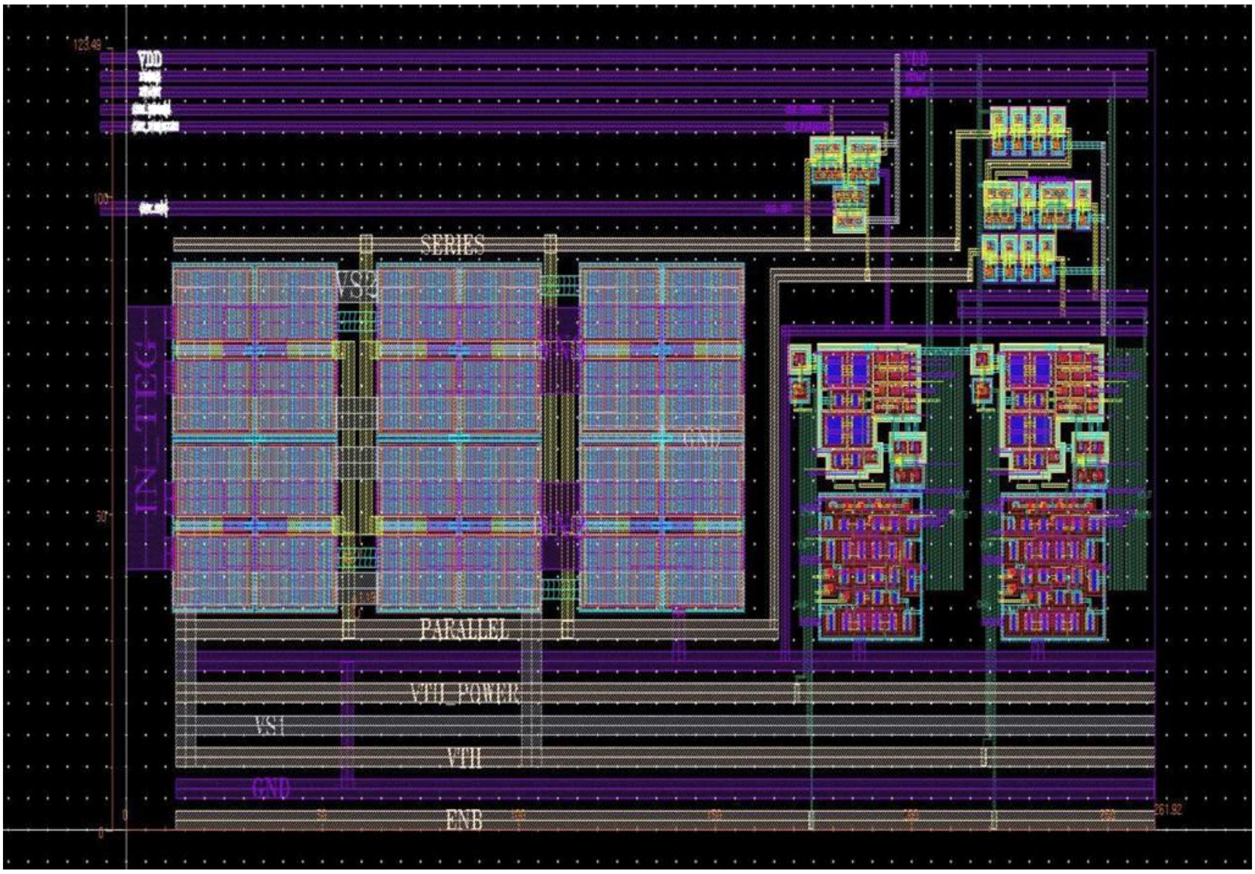


Figure 2.5: Layout of TEG its control logic

2.2.2 Maximum power point tracking(MPPT)

As known from the circuit theory, maximum power is delivered from a source with internal resistance to a load when the resistance of the load is equal to the internal resistance of the source. If the source resistance and the load resistance are di erent then there will be more loss in power delivered to the load by the source.MPPTmodule mainly works to make the source supply maximum power that it can.MPPT is a full on electronic system that varies the electrical operating point of the modules so that the modules are able to deliver maximum available power. For solar input, maximum power point will be shifted depending on the intensity of light available whereas for a TEG source maximum power point will be varying based on the change in the temperature difference between the plates of the transducer. In the same way as for TEG and solar, the maximum power point for the piezo will vary depending on the change in the pressure across the plates. There are many algorithms developed for MPP tracking to extract maximum power from source such as hill climbing, perturb and observe, fractional open circuit voltage etc. The method that works well for the type of transducer will be decided based on the complexity, efficiency etc. of the MPP controller circuit for that source. Figure 2.10 and figure 2.11 have the description of power characteristics of TEG and piezo sources.

For the present system, with the TEG input voltage range between 10mV-700mV the change in the internal resistance of the transducer will not be huge allowing us to take the resistance value to be a constant of 3.9 ohms.MPPT for TEG source can be achieved by following the below mentioned equation.

Rteg is the internal resistance of the TEG source, fs is the switching frequency of the converter, L is the inductor value in the converter. As mentioned above the internal impedance of the load should be equal to the impedance of the load to attain a maximum power transfer from source to load. In an energy harvester system, the impedance of the converter seen from the source depends on the frequency with which converter is switching. The above mentioned formula gives a relation between the transducer internal frequency and the switching speed of the converter. The MPP voltage for TEG will be generally 0.5 times the open circuit voltage. To attain MPP for TEG source the frequency of the converter need to be fixed based on the resistance offered by the source and the inductance value of the converter. For a transducer with an internal impedance of 3.9ohms and inductance value of 40uH, the switching frequency of the converter is to be 22KHz to achieve MPP.For the system designed where a multi TEG array has been used to power it, the frequency of the converter need to 4kHz and 38kHz when the individual sources are connected in parallel and series respectively. The logic to switch the frequency between 4 kHz and 38 KHz has been developed so as to attain maximum power transfer. When the converter is powered with TEG, the low side switch is connected to a clock frequency of 4 kHz or 8 KHz with a 50 percent duty cycle. Figure 2.13 describes the MPP method followed for TEG array.

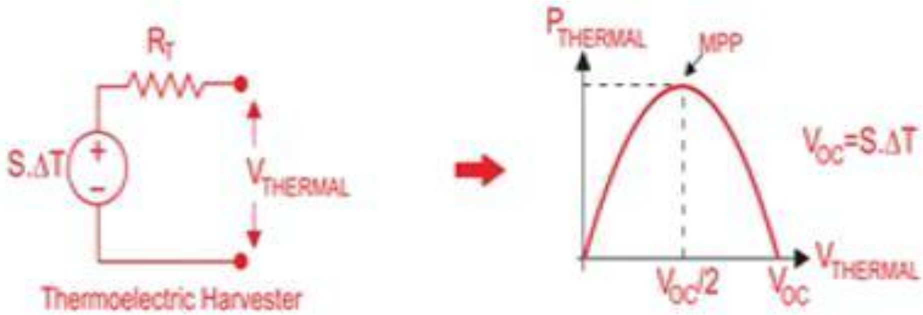


Figure 2.6: power characteristics of a TEG source

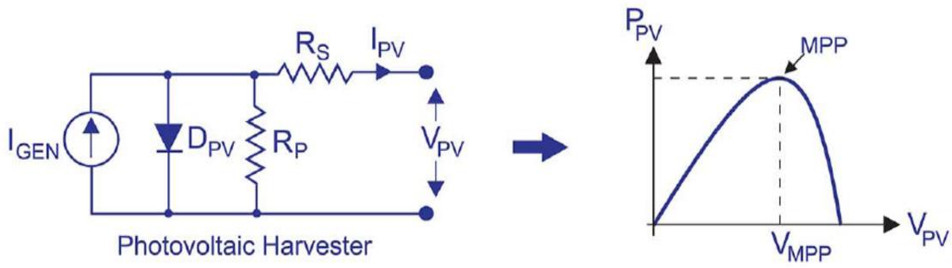


Figure 2.7: power characteristics of a PV source

For a PV electric transducer the MPP voltage will be 0.5 times the open circuit voltage same as a TEG source. The MPPT for piezo has been done through Fractional open circuit voltage (FOCV) method where the transducer is disconnected from the converter when the voltage of the transducer goes below half the open circuit voltage. An analog comparator always compares the output voltage of piezo transducer with 0.5 times its open circuit voltage and outputs a HIGH/LOW signal which is fed to the next stages of the system. If the output is HIGH then the piezo source is connected to the converter or will be disconnected from the system.

Figure 2.12 briefly describes the connection of the piezo transducer to the converter.Voc- PV being the open circuit voltage of the PV transducer. PVsource is connected to the converter when the voltage across piezo voltage source is greater than half the open circuit voltage. To summarize the MPPT techniques used for TEG and PV, converter switching frequency of 38KHz for series connection of TEG sources and 4KHz for parallel connection of TEG sources has been decided based on the output impedance offered by the converter for the respective frequencies and for PV FOCV method has been used to track maximum power point for the sources. Overview of the MPP technique for TEG can be seen from the figure

$$fs = Rteg/8L$$

------ [8]

Figure 2.8: MPP equation for TEG source

No. of sources	Rteg	Converter switching frequency	MPP method	Equation
1	3.9ohms	12.5KHz	Constant converter switching frequency	$fs = Rteg/8L$ ----- [8]
3 : series connection	11.7ohms	38KHz		
3 : parallel connection	1.3ohms	4KHz		

Figure 2.9: MPP methodology for TEG array

2.2.3 Power converter

The power from the sources such as TEG, piezo, solar and RF are in uW/mW ranges which are not sufficient to supply loads which need power in mW/W ranges. Micro-scale energy harvesting needs to boost the input power available to higher power ranges. Module that performs the work of converting lower powers to higher powers or vice-versa is called a converter. Converter can be inductor based or inductor-less (charge pump).The choice of the converter is made taking many parameters into account such as efficiency, area etc.

The first and foremost limitation of inductor based converters are the cost and size of inductor in the converter. To deal with the cost constraint, cheaper inductors are used that dissipate more power and hence degrade power conversion efficiency. On the other hand inductor less topologies use only two small and low cost capacitors instead of expensive inductors. Inductor less topologies have many advantages over inductor based topologies such as cost, area providing an ultra-integrated on chip solutions for lower current levels. The main advantage of inductor based converter over inductor less converter is its high power conversion efficiency for low input powers.

When the input power to the converter is low and variable, inductor based topologies take advantage over charge pump converters whose power efficiency will be very low in such cases. Microscale energy harvesting system thus prefer inductor based topologies over charge pump topologies when the input power available to the converter is less. Lots of work has been carried out in designing power converters with multi inputs or multi outputs [5] or both have been done across the world.

For the MIMO system designed as the project work, input powers for the two sources TEG and piezo vary from uW-mW leaving us with the inductor based converter as an option for having high power conversion efficiency. Inductor based power DC-DC converters can be boost, buck or buck- boost depending on the input and output voltage values. A boost converter will boost the input voltage to higher values and supply it to the loads where as a buck converter will buck the input voltage to lower values and supply to the load. A buck-boost converter operates in both boost mode and the buck mode depending on the voltage available at the input and the voltages required at the output. Inductor based DC-DC converters can work in continuous conduction mode (CCM), Discontinuous conduction mode (DCM) etc. In CCM the inductor is not fully discharged where as in DCM inductor is fully discharged and inductor current becomes zero for a moment or for a duration of time. For the widest possible operating range DCM mode is preferred over CCM mode due to its high stability and single pole transfer function between input and output. Taking all parameters into account DC-DC converter for the designed hybrid energy harvesting system is an inductor based converter working in DCM mode due to its wide operating range.

The Figure 2.10 is an inductor based DC-DC converter in boost mode with an inductor and two switches that switch one at a time, charging and discharging the inductor alternatively. It also has input and output capacitor that charge from the source and maintains an approximately constant voltage across the load respectively. When the low side switch is ON, the inductor stores energy from the source. When the high side switch is ON the voltage across the source in addition to the stored energy in the inductor is applied across the load making the load voltage higher than the source voltage. The impedance offered by the converter to the source depends on the switching frequency of the converter and values of other elements in the converter. The two switches should be non-overlapping so as to prevent a short between load and ground. Figure 2.11 is a buck converter having two switches, an inductor and two capacitors .It differs from the boost converter only in the positioning of switches that switch accordingly to make the output voltage across the load lesser than the input voltage. The impedance offered by the converter depends on the switching frequency and the values of the other components in the converter topology. The two switches should be non-overlapping so as to avoid a short between the source and ground. Buck-boost converter performs both boost and buck operation depending on the voltage requirements of load and the available source. Figure 2.12 is a buck boost DC-DC converter.

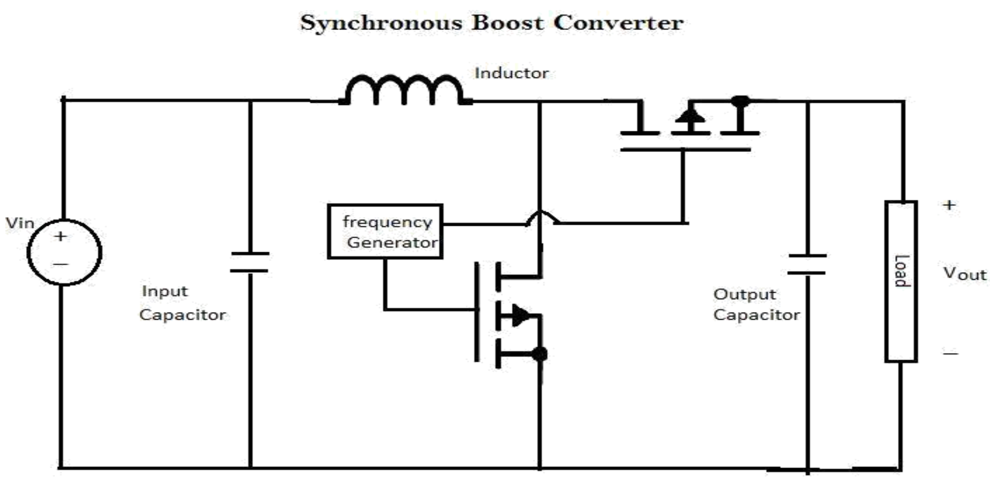


Figure 2.10: Synchronous Boost converter

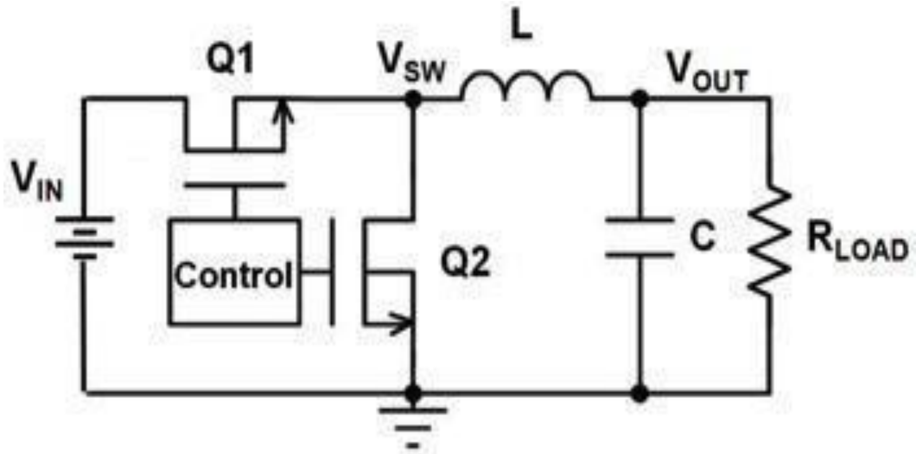


Figure 2.11: Synchronous Buck converter

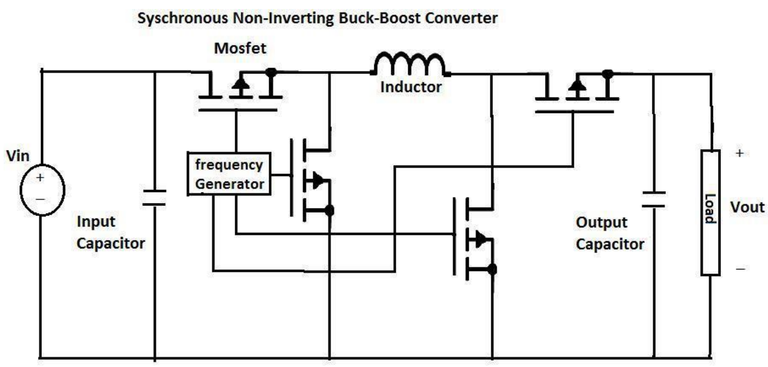


Figure 2.12: Synchronous Buck Boost converter

For the hybrid energy harvesting system designed the converter is a buck boost converter working in DCM mode. A brief explanation is given below to justify the above statement. The input sources for the DC-DC converter are TEG and piezo having voltages ranging from 2mV-700mV for TEG and 18uA-280uA (212mV-3.3V) for piezo respectively. The output capacitor need to be charged to a voltage of 1.8V which clearly states the need of a buck-boost converter. It works in boost mode for TEG because of its low input voltages than the required output voltage where as it works in both boost and buck mode for piezo due to its wide input voltages where some input voltages are higher than the output voltage needed. The high side switch is a PMOS because it needs to pull up the node to higher voltages whereas the low side switch is an NMOS because the node need to be pulled down to 0V.The frequencies with which the both switches operate varies depending on the input that is connected to the converter i.e. frequencies vary with TEG or piezo source that is getting connected. The two switches need to be non-overlapping so as to prevent a short between load or source depending on mode of operation. The value of inductor is 40uH that suits well for both TEG and piezo sources. The value is fixed to be 40uH taking many parameters into account such as saturation of inductor etc. for both the sources. The power MOSFETs are in mm size so as to have less switching and conduction losses. Fig 2.18 and 2.19 are the schematic and layout of the power switches in the designed hybrid energy harvesting system.

In the buck-boost converter shown in the above schematic view, switches S1 and S2 are the power switches which connect either TEG or piezo depending on the source availability and the inductor current. When the converter is in boost mode, S1/S2 will be ON depending on source and S5 is OFF whereas switches S3, S4 are the low side NMOS and high side PMOS switches respectively. When the converter works in buck mode for piezo source S4 is continuously ON where S2, S5 switch alternatively for the desired operation. The clocks needed for the switching of the mosfets are generated from the combination of source selection blocks and is briefly described in the next part. Inductor current for different modes of working of system can be seen from the figure 2.21. Fig 2.20 gives information about the power converter specifications in the designed system.

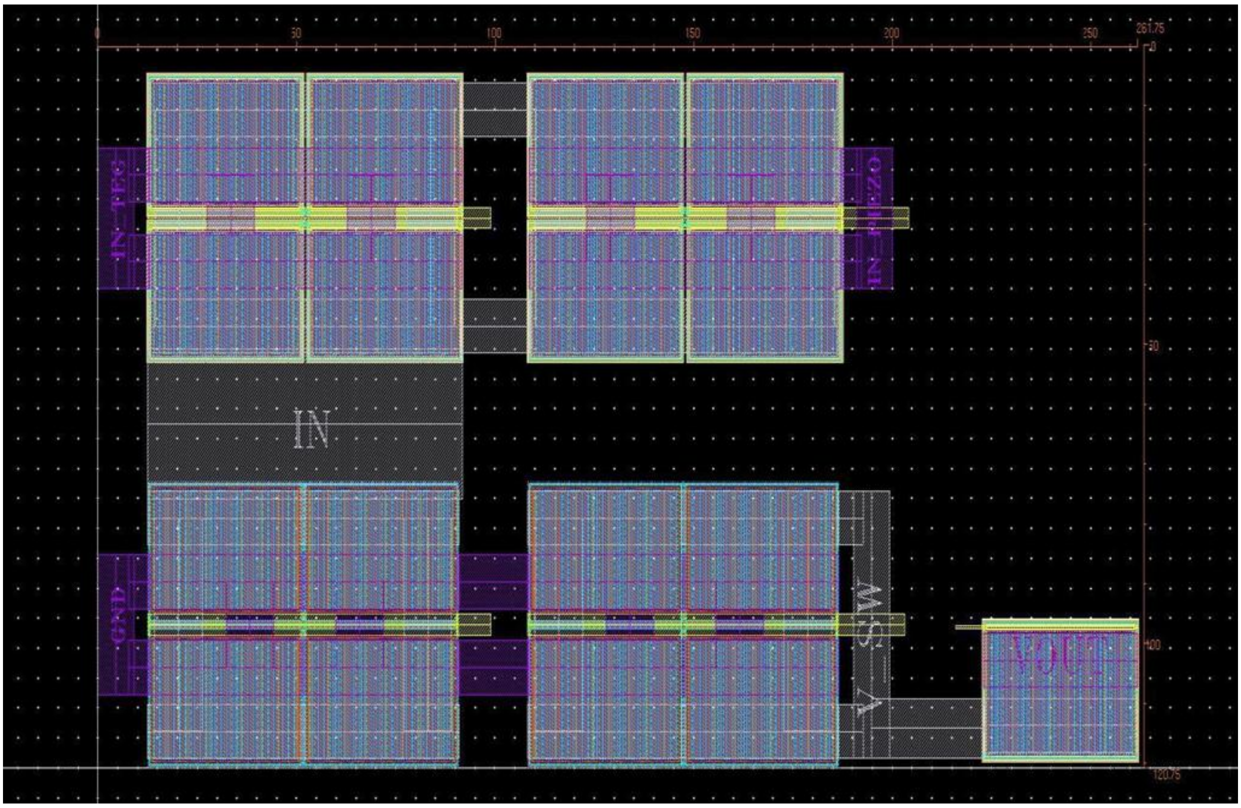


Figure 2.13: Layout of power switches

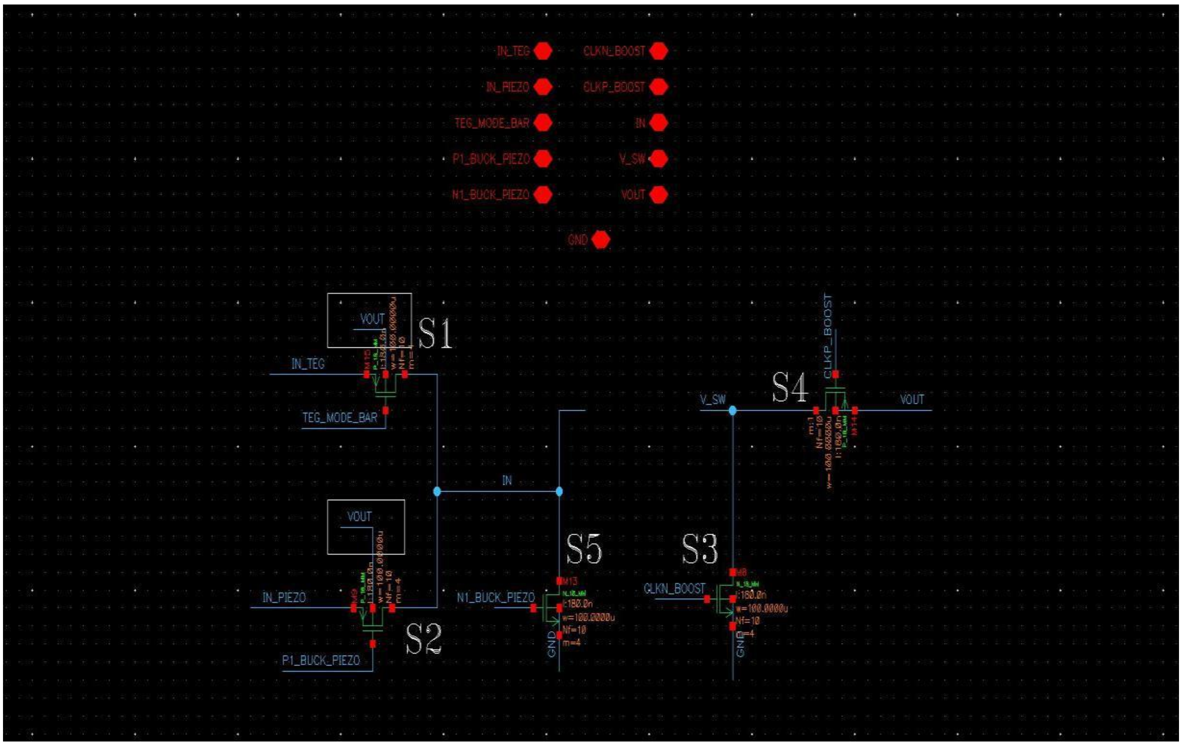


Figure 2.14: Schematic of buck boost power converter

2.2.4 Digital controller

The block that generates the clock signals for the switches in the DC-DC power converter is a digital controller. In the designed hybrid energy harvesting system digital controller comprises of a source selection block that turns on S1/S2 or neither depending on the power availability at the input and a MOS driver logic block that generates the clocks for the other power MOSFETs in the DC-DC power converter. Different DC-DC converters with as many inductors as sources, time division multiplexing using a single inductor that is shared between all the sources are some of the methods to do hybrid energy harvesting. The present multi input hybrid energy harvesting system utilizes the concept of using the dead time of the inductor current for harvesting energy from the second source. In depth explanation for the above mentioned concept is given below. TEG input source voltage for the designed system will have a range of 2mV-700mV.When using an array of three TEG sources having all same voltage outputs and having an internal impedance of 3.9ohms each, there exists two modes of connection among all the three TEG sources i.e. series or parallel. When there is a huge temperature variation, the voltage across each TEG source increases to higher values leaving an option for them to be connected in parallel there by increasing the input power by increasing the net input current to the DC-DC converter.

Source	Input range	Output	Converter	Mode of converter operation	Converter design challenge	Design specifications
TEG	12mV – 700mV	1.8V	Boost	DCM	1.Optimal inductor value 2. Switch sizing	L=40uH
Piezo	18uA-280uA (212mV – 3.3V)	1.8V	Buck - Boost	DCM		

Figure 2.15: Power converter

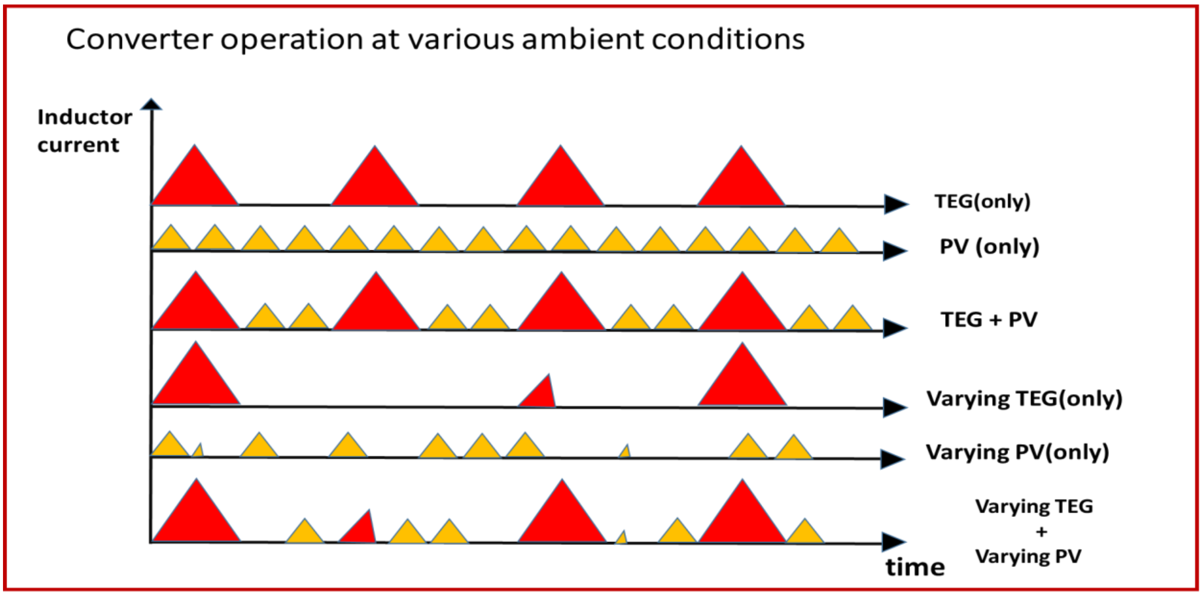


Figure 2.16: Converter operation at various ambient conditions

When the temperature difference is less the output voltage across each source is also less and the three sources are connected in series there by increasing the input voltage resulting in an increase in the input power. When the sources are connected in series the impedance of the three sources is increased to 11.7ohms resulting in a switching frequency of 38 KHz for the DC-DC converter to track maximum power point. In the same way when the sources are connected in parallel the impedance offered by the TEG array is 1.3ohms resulting in a switching frequency of 4 KHz for the DC-DC converter to track maximum power point. Clocks of those frequencies with 50 percent duty cycle are to be given to the high side and low side switches of the boost converter when TEG array having sufficient power to supply to the converter is connected. The inductor charges during the first half cycle of the clock signal while it discharges and stays at zero (called dead time of inductor current) in the second half cycle of the clock signal. PV source works with a clock frequency of 40 KHz with FOCV as the MPPT method. The above mentioned values for the clock frequencies for the two sources TEG and PV clearly state that the time period for TEG source if far greater than the time period for piezo source. The idea of using the dead time of the inductor current after inductor discharges its stored energy from TEG source for piezo source is the main concept of designing the present hybrid energy harvesting system.TEG source is given high priority over piezo source due to its high energy densities. Figure 2.10 is a flowchart for designing digital controller for hybrid energy harvesting system developed.

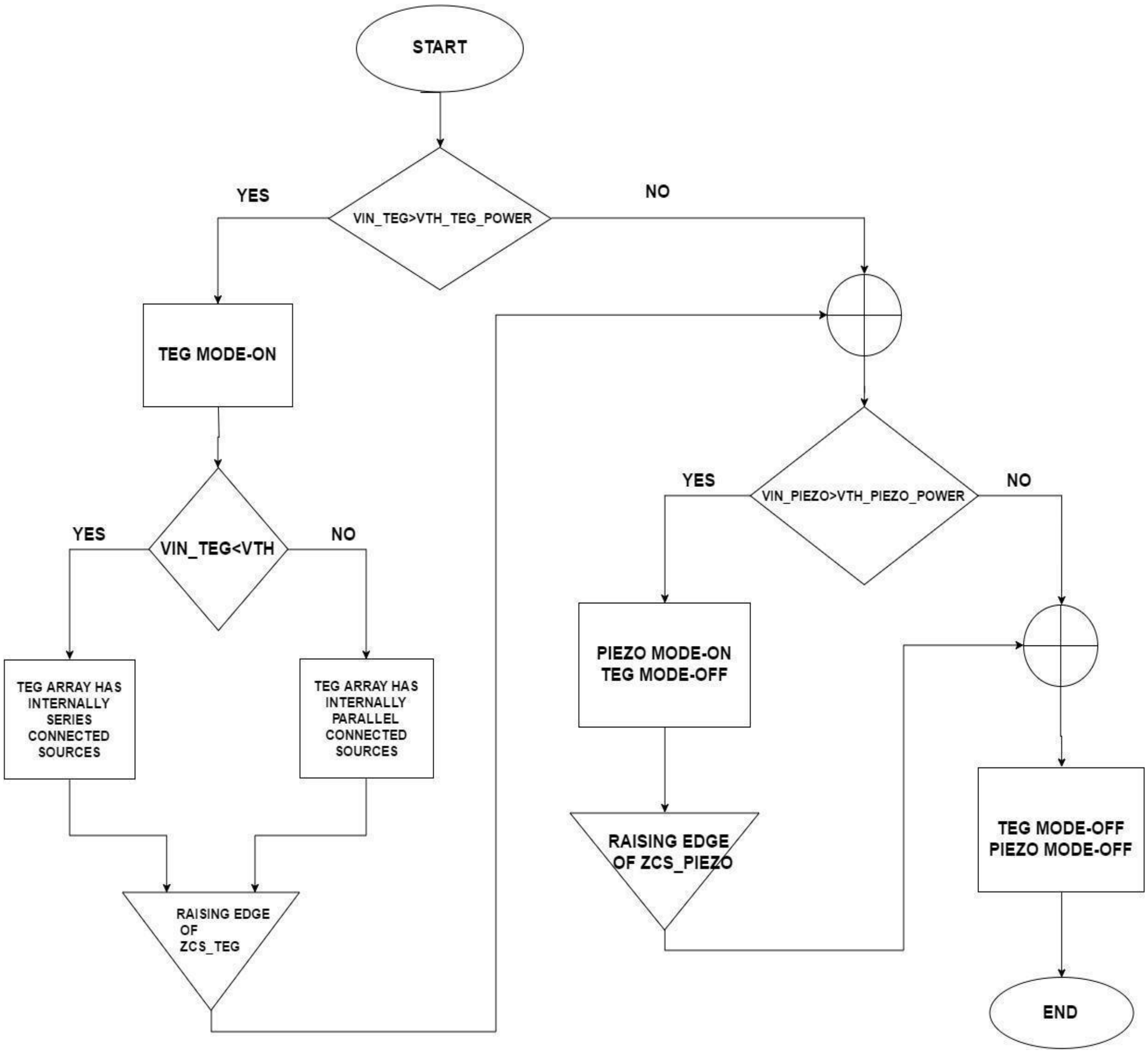


Figure 2.17: Flow chart of digital controller

VIN-TEG denotes the voltage across the TEG array,VTH-TEG-POWER is the threshold to compare TEG voltage.TEG-MODE the signal that specifies if TEG source is connected to the converter, PIEZO-MODE is the signal that specifies if PIEZO source is connected to the converter,ZCS-TEG and ZCS-PIEZO are the two ZCS signals that are generated using a ZCS block for the two clock signals CLK-TEG and CLK-PIEZO respectively.TEG source always works in boost mode where the signals for the high side PMOS and low side NMOS switches are generated from MOS driver logic block. Piezo source can work in boost or buck mode depending on its input voltage and the clock signals are generated from MOS driver logic block. The high side and low side switches are to be non-overlapping so as to prevent short between source to ground or load to ground. Figures 2.23 and 2.24 are the layouts of source selection block and MOS driver logic block. Power for digital controller block is supplied from the load capacitor once it reaches 1V from the start up circuit. An analog comparator continuously compares the voltage on the capacitor and outputs a digital HIGH or LOW signal. If the output of the comparator is high then the capacitor did not reach 1.8V yet and hence the system should work. If the comparator gives a LOW signal, it states that the voltage across the load capacitor reached 1.8V and hence the system should stop functioning. Working of the system is aborted by stopping the free running clocks for TEG (38 KHz/4KHz for series/parallel) and Piezo (200 KHz). This is done using AND gates which has the comparator output as one of their inputs and free running clocks as their second outputs.

2.2.5 Load

Load can be a battery or a supercapacitor or it can be an entirely different system that Performs some other function i.e. a load can be resistive or capacitive type. Load is decided based on the specifications and the driving capability of the system. The hybrid energy harvesting system designed has a 10uF capacitor as load which is needed to be Charged to 1.8V and then can be disconnected.

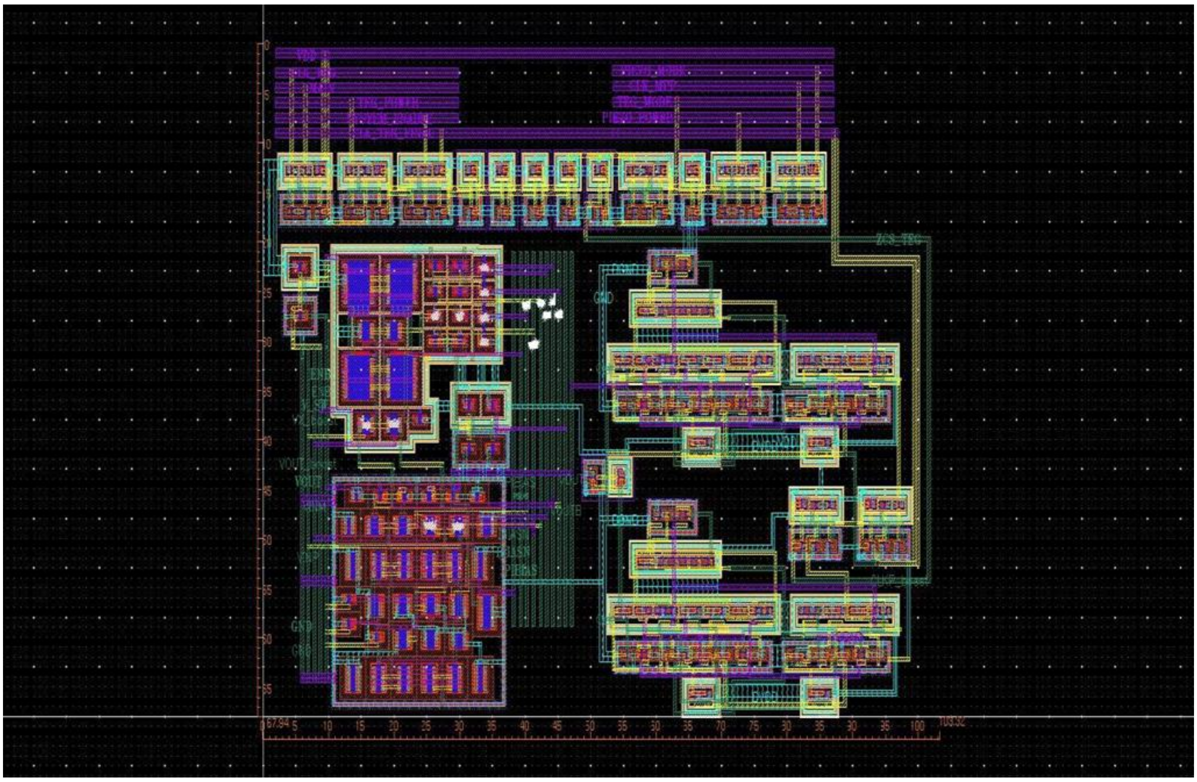


Figure 2.18: Layout of source selection module

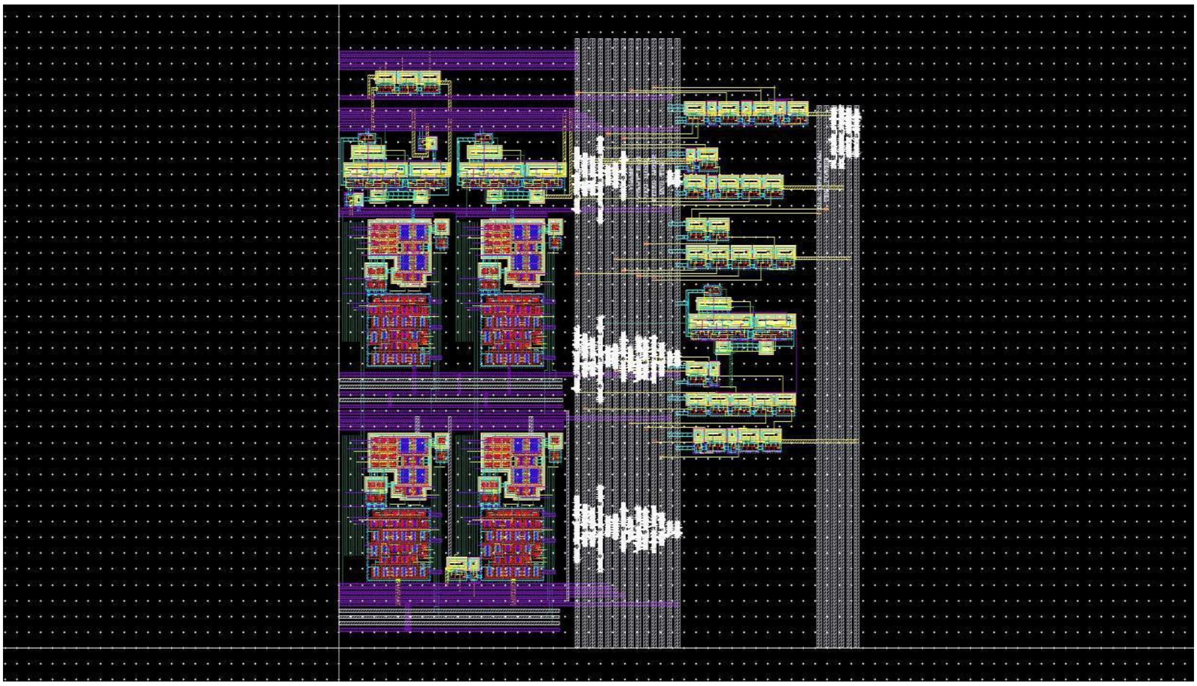


Figure 2.19: Layout of MOS driver logic module

Chapter 3

Compact multi source harvesting techniques
design of different blocks

3.1 Current Reference

Compact Current Reference circuit is need in system to generate all bias voltages and bias currents in the circuit. Below circuit is 2nA current reference circuits which is used to mirror remaining currents in the circuits to give it as bias currents to different circuitary. Below is Schematic of the implemented current reference, with start up circuit, the circuit provides a reference current of 2 nA from a variable VDD of 1 V to 1.8 V

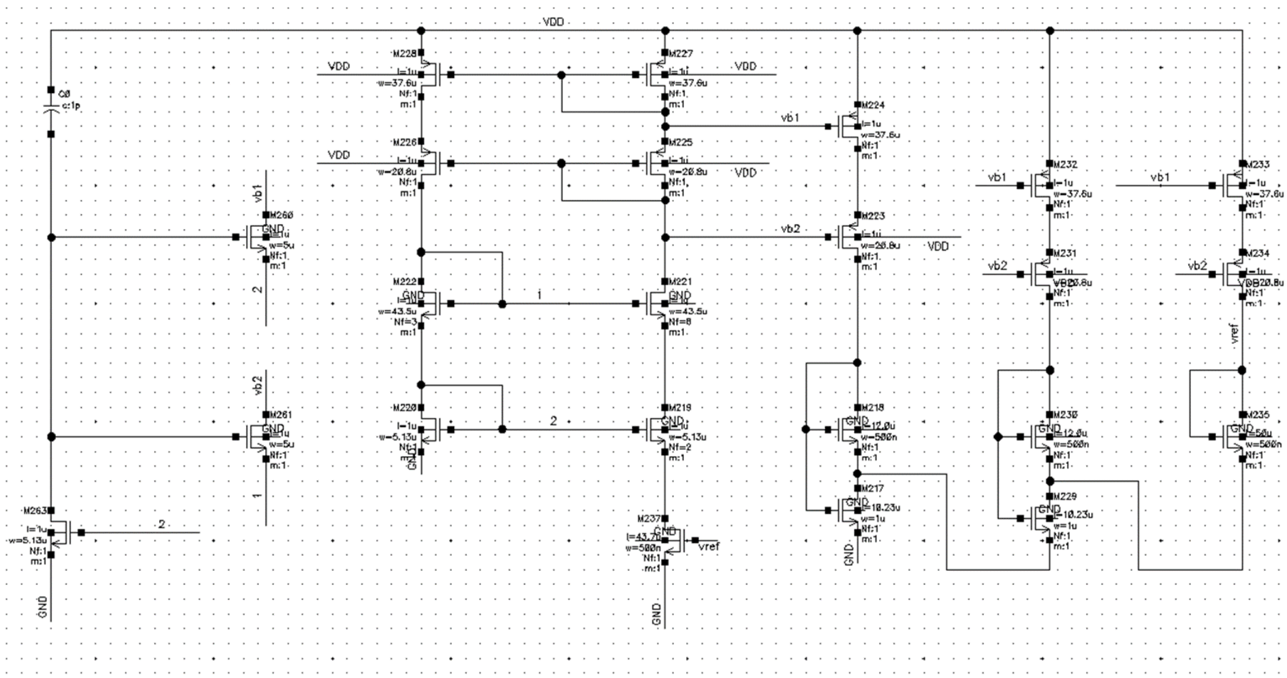


Figure 3.1: Current reference circuit with start-up

Performance of the current reference implemented with respect to variation in supply voltage, the supply is varied from 0 V to 2.5 V, from 0.8 V, the reference current is constant

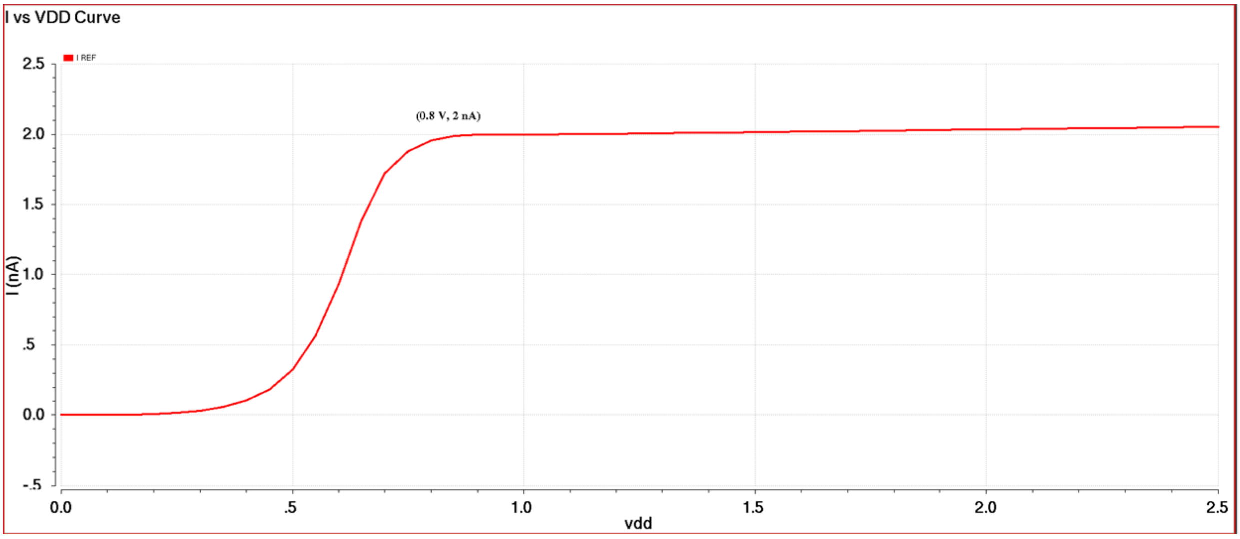


Figure 3.2: Current reference performance with variation of VDD

Performance of the current reference implemented with respect to start-up condition.with out start-up circuit won't turn on so start-up circuit is added to make circuit to turn on below graph represents current curves in the absence of start-up and in the presence of start-up in this circuit start-up problems also addressed.
Experiment for verifying the start-up condition, it can be seen that with start up the system starts at 10 ms whereas the system is unable to start with ramp VDD without the startup

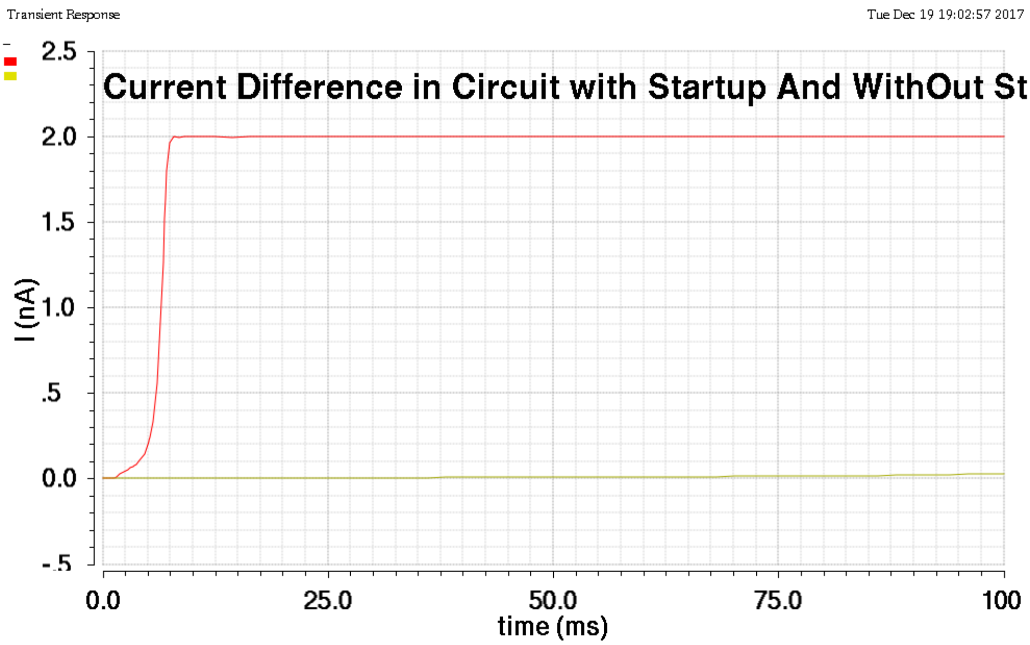


Figure 3.3: Current reference performance with start-up and with out start-up

3.1 Zero Current Switching comparator

In the circuit we need ZCS comparator to detect zero inductor current. So that we can take care on unwanted discharge of load which finally results into efficiency improvement.

For that comparator duty cycled enable is there so that we can turn on the comparator at particular times when we want . because of duty cycled clock comparator the powerconsumption in the circuit reduced a lot.

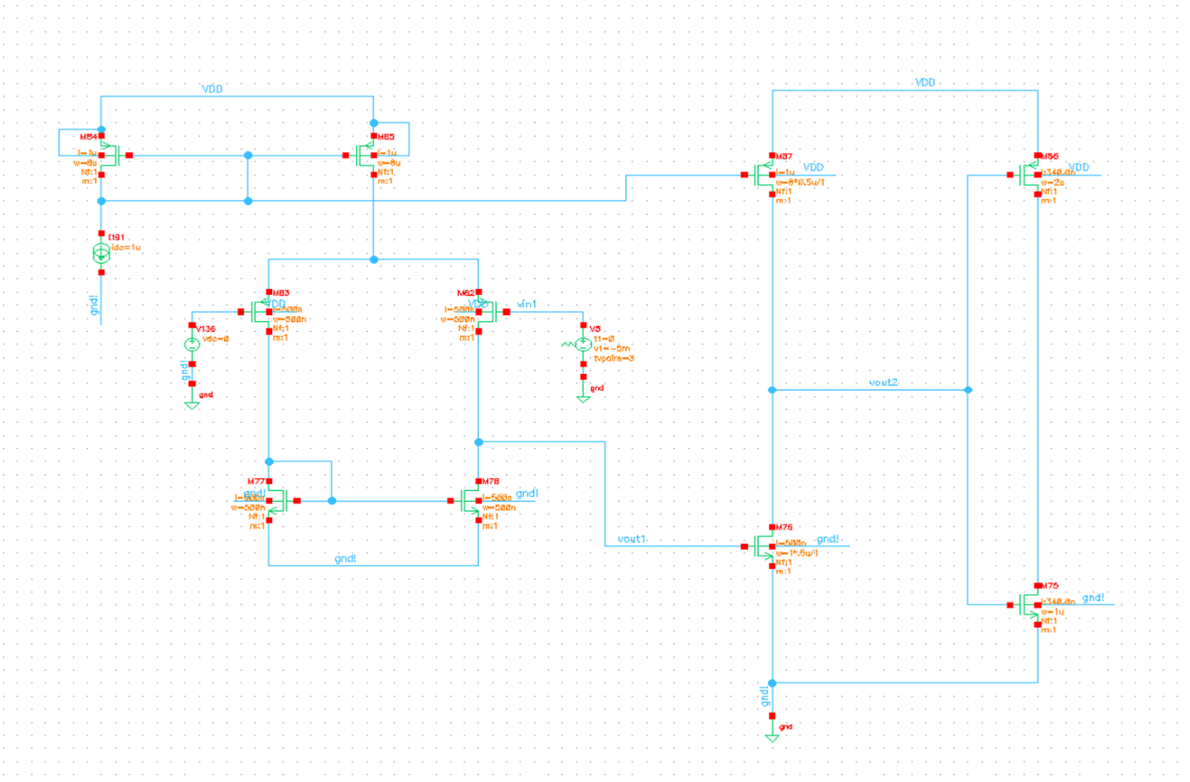


Figure 3.4: ZCS comparator Schematic

<u>Specifications:</u>

- Variable Vdd from 1 V to 1.8 V
- > 60 dB gain
- >800 kHz Bandwidth
- ICMR = 0 V
- Current consumption – 1.5 uA
- Duty cycled to reduce the average power

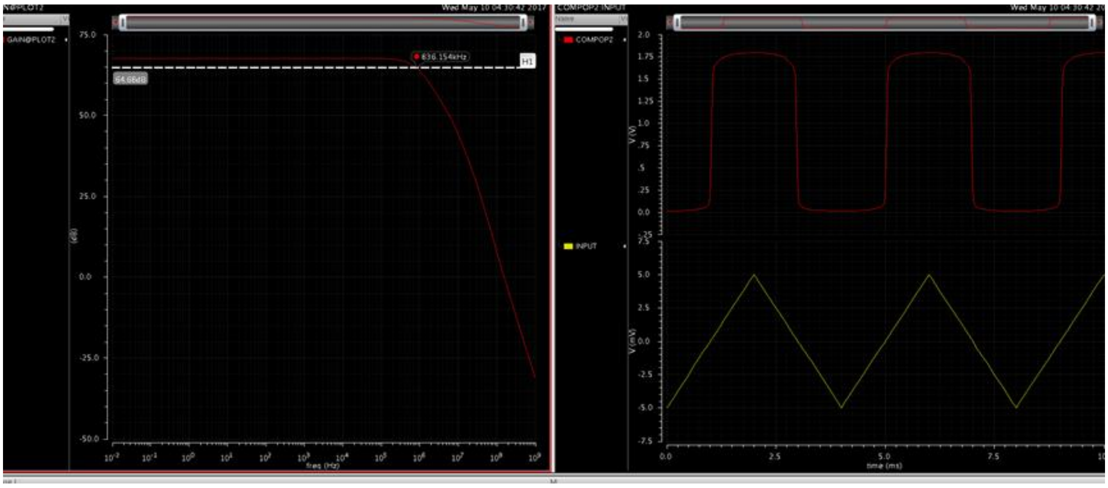


Figure 3.4: Typical simulation – Transient & AC – 64 dB gain and 830 kHz BW

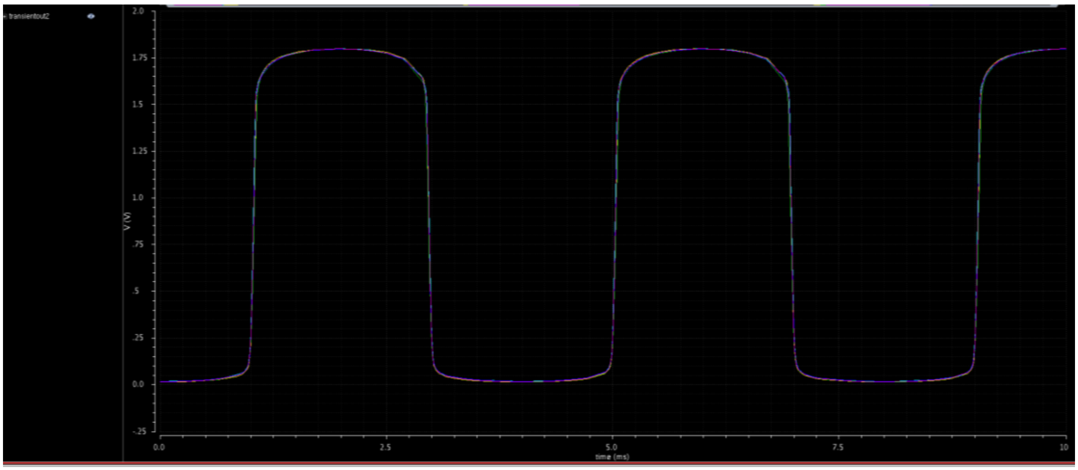


Figure 3.5: Corner simulation - Transient

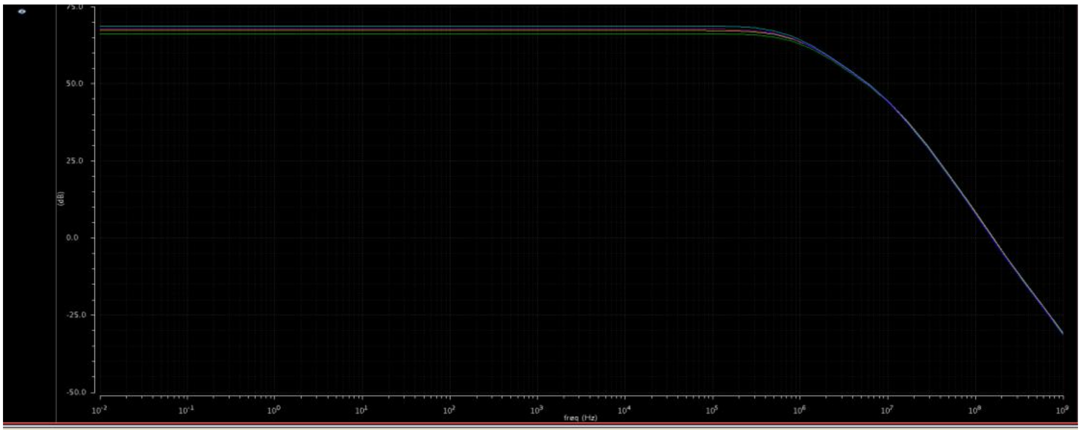


Figure 3.6: Corner simulation – AC

3.3 LDO FOR MULTIPLE VDD

The purpose of this **Low Drop out Regulator (LDO)** is to produce multi range output supplies and current driving capability in the range from Nano to Micro amperes range. At the same time high Supply variations to the output (PSRR) and better Loop gain phase margin (PM) for loop stability has been achieved with low quiescent current. For better phase margin (PM) proper compensation method has been adopted. All the performance parameters for this LDO are tabulated in the table below.

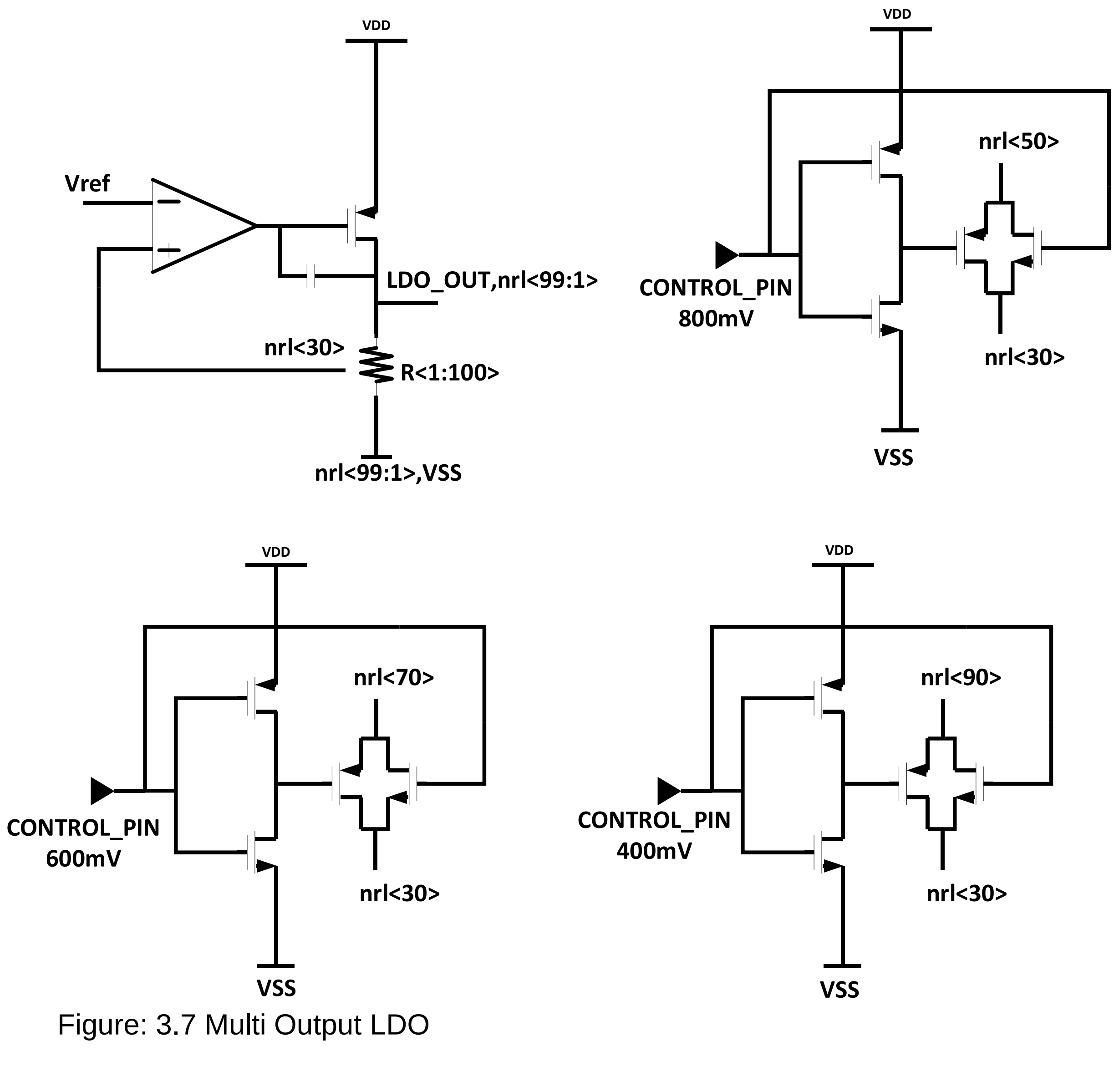


Figure: 3.7 Multi Output LDO

OUTPUT VOLTAGE RANGE (in Volt)	**1, 0.8, 0.6, 0.4**
OUTPUT DRIVING CURRENT (in uA) MAX	**100**
QUEISENT CURRENT (in nA)	**100**
PSRR (in dB) @10 KHz	**-28**
PHASE MARGIN (PM in degree)	**80**

Table: 3.1 LDO Performance Parameters

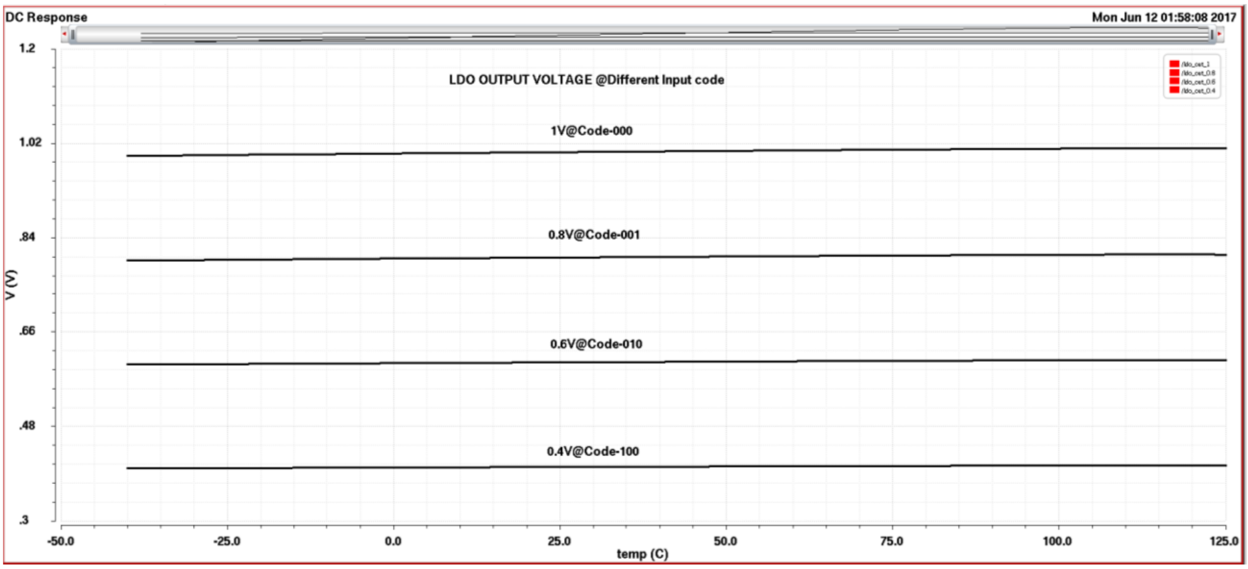


Figure: 3.8 LDO Output Voltage VS Temperature

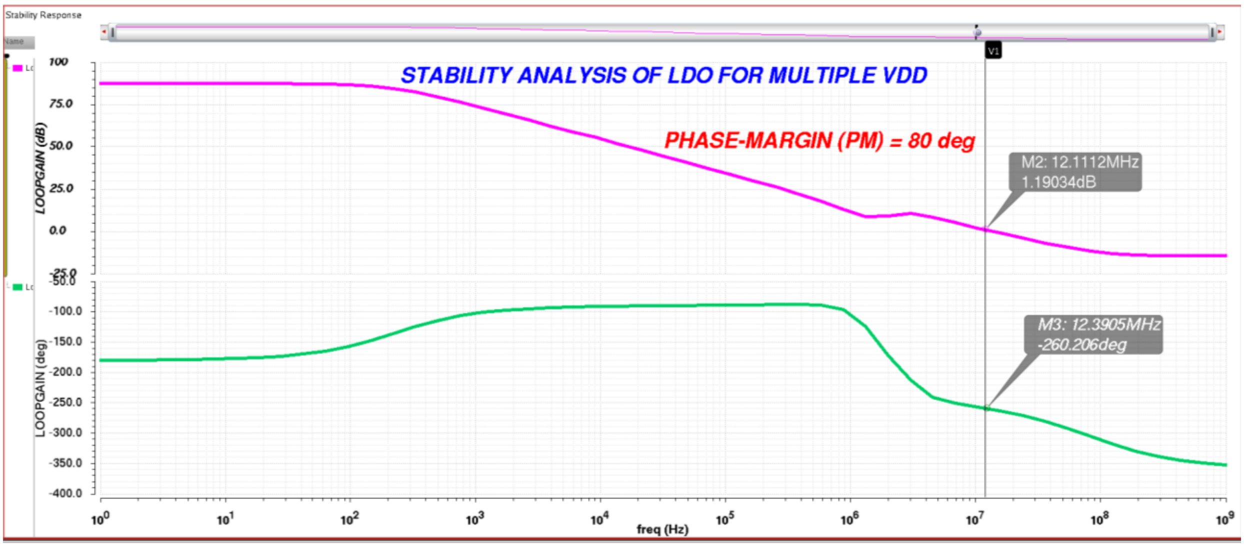


Figure:3. 9 LDO Loop Gain Plot (Gain & Phase)

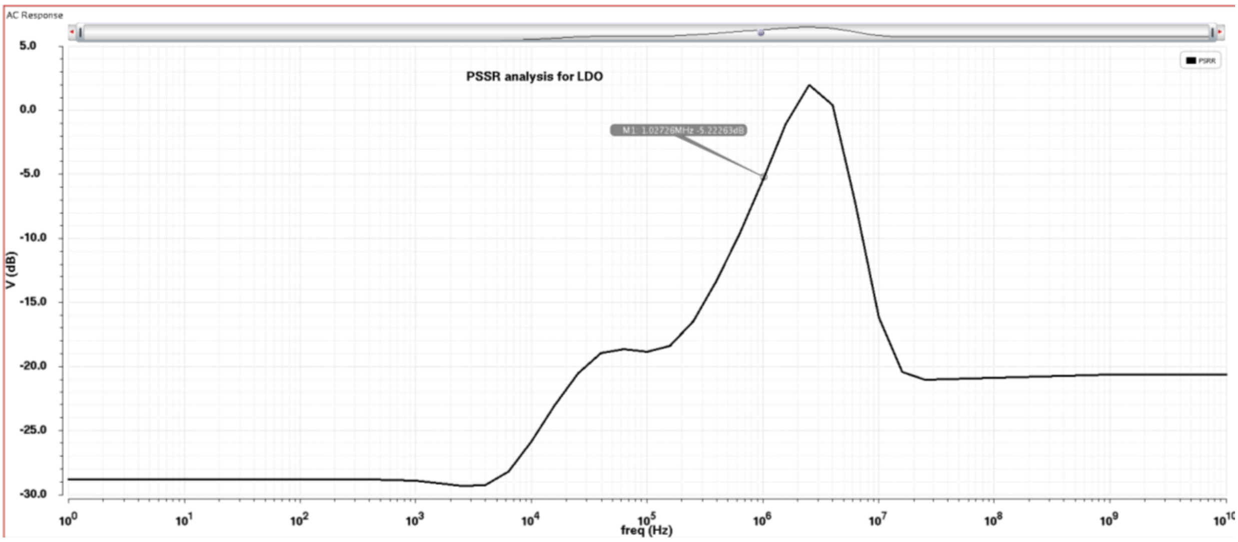


Figure: 3.10 LDO PSRR Plot

Chapter 4

Simulation results and verifications

There are many cases where the functionality of the system need to be checked. The table below gives an outline of various conditions in which the system should work.

The below mentioned simulation results have the waveforms for the inductor current and the mode in which the system is operating i.e. TEG or PV mode. The waveforms also give information about the way in which both TEG& PV sources are connected

4.1 Results

The system has been designed in UMC technology, 180nm process note in cadence virtuoso. Schematic results for various cases tested have been described below.

4.1.1 TEG having minimum voltage(20mV) while PV doesn't have power

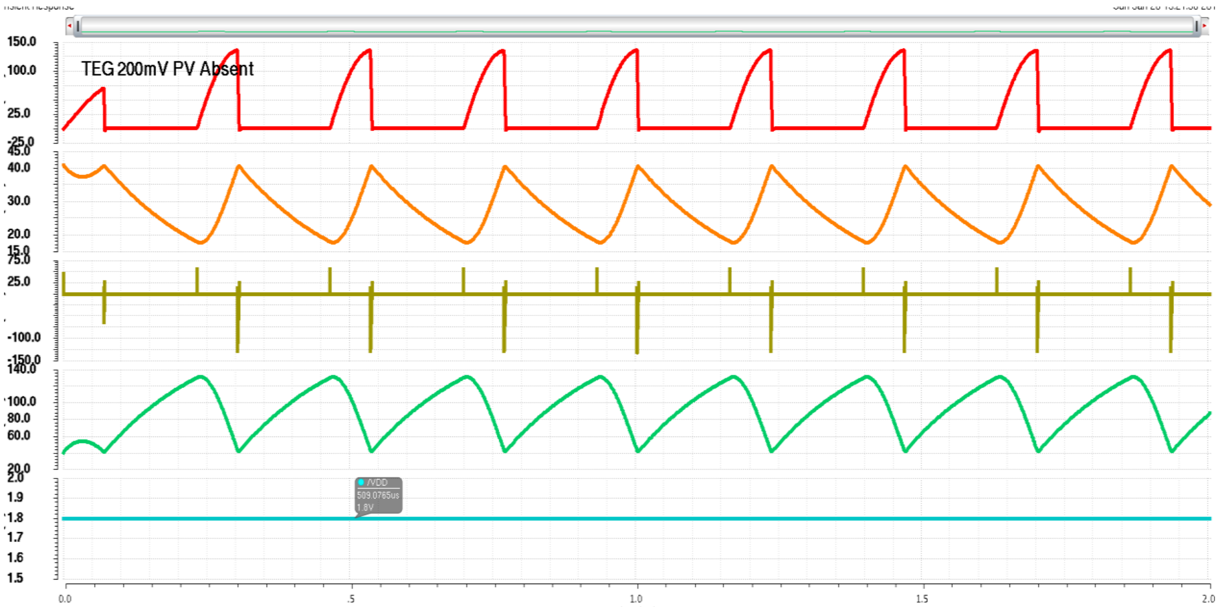


Figure 4.1: TEG-minimum power and PV-no power

The above plot are the results for the system working when TEG source has a minimum voltage and Photo Voltaic does not have power to supply the load. It can be observed from the above graph that TEG voltage across a single source is 20mV and the system is working i.e. when inductor is getting charged and discharged we can observe the average TEG voltage being around 20mV nearly close to MPP.It can also be seen that the output voltage is being settled to 1.8V. When the output voltage reaches 1.8V the input voltage reaches open circuit voltage as the system doesn't take any power from the source.

4.1.2 TEG having maximum voltage (200mV) while PV doesn’t have power

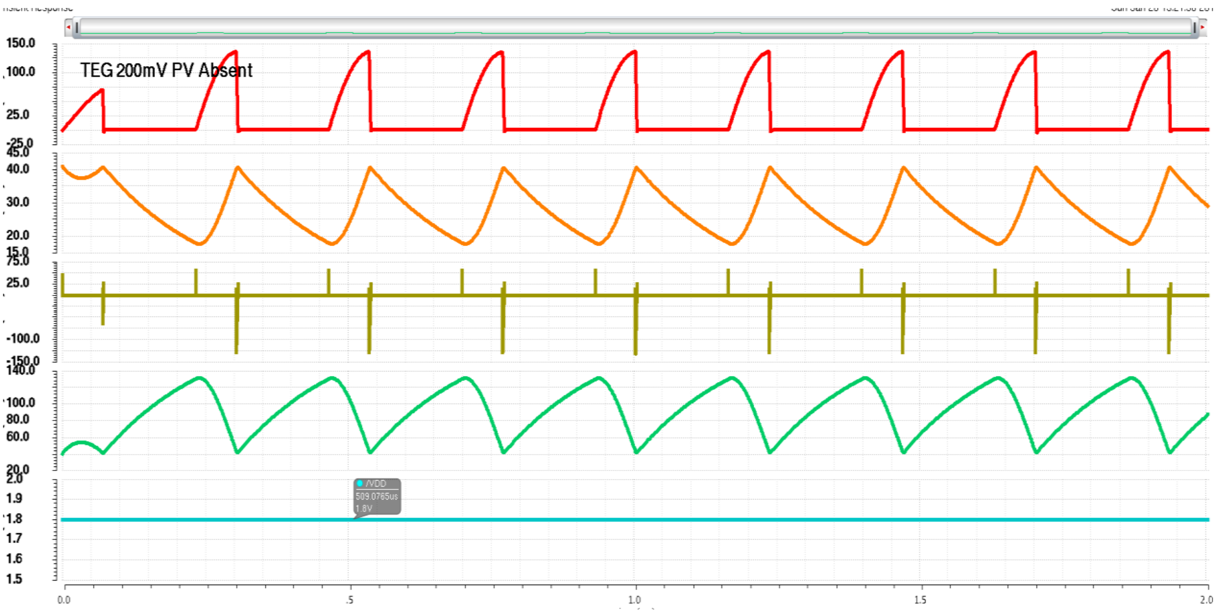


Figure 4.2: TEG-maximum power and PV-no power

The above plot are the results for the system working when TEG source has a maximum voltage 200mV and Photo Voltaic does not have power to supply the load. It can be observed from the above graph that TEG voltage across a single source is 20mV and the system is working i.e. when inductor is getting charged and discharged we can observe the average TEG voltage being around 200mV nearly close to MPP.It can also be seen that the output voltage is being settled to 1.8V. When the output voltage reaches 1.8V the input voltage reaches open circuit voltage as the system doesn’t take any power from the source.

4.1.3 TEG doesn’t supply any power while PV supplying Minimum power to the system

It can be inferred from the below graph that without TEG power and with minimum PV power the output voltage is charged to a voltage of 1.8V.It can also be seen that the PV source is at MPP when the system is working. The maximum inductor current is less for the PV source when compared to maximum inductor current for TEG source.

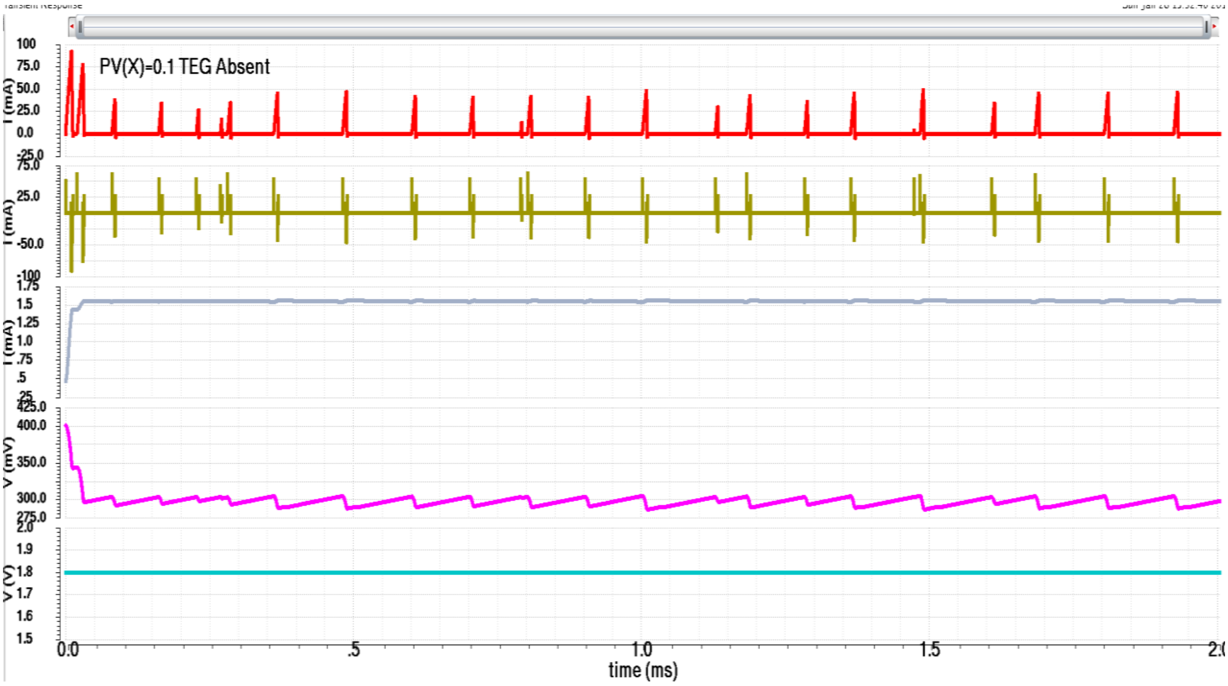


Figure 4.3: TEG-No power and PV- Minimum power

4.1.4 TEG doesn't supply any power while PV supplying Maximum power to the system

It can be inferred from the below graph that without TEG power and with maximum PV power the output voltage is charged to a voltage of 1.8V. It can also be seen that the PV source is at MPP when the system is working. The maximum inductor current is less for the PV source when compared to maximum inductor current for TEG source.

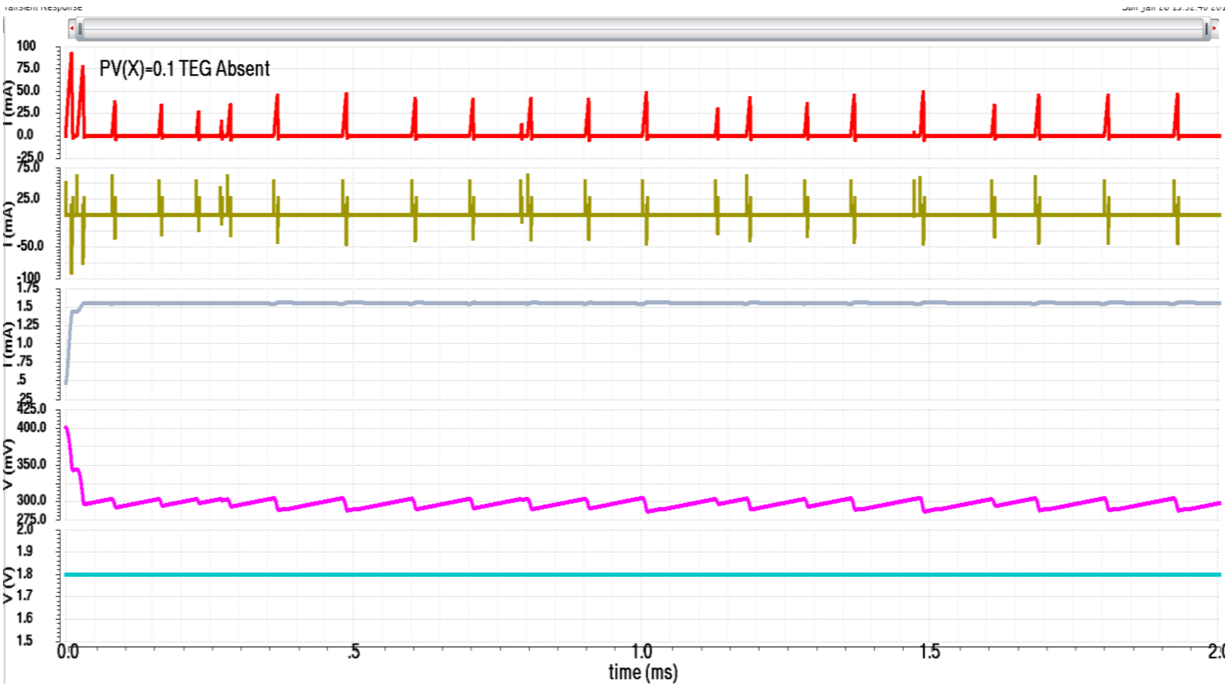


Figure 4.4: TEG-No power and PV- Maximum power

4.1.5 Both TEG and PV sources supply minimum power to the system

TEG and PV source has minimum power to supply to the system. It can be seen clearly that PV is at MPP till the time it supplies power to the system.The load being charged to 1.8V can also be seen from the graph.

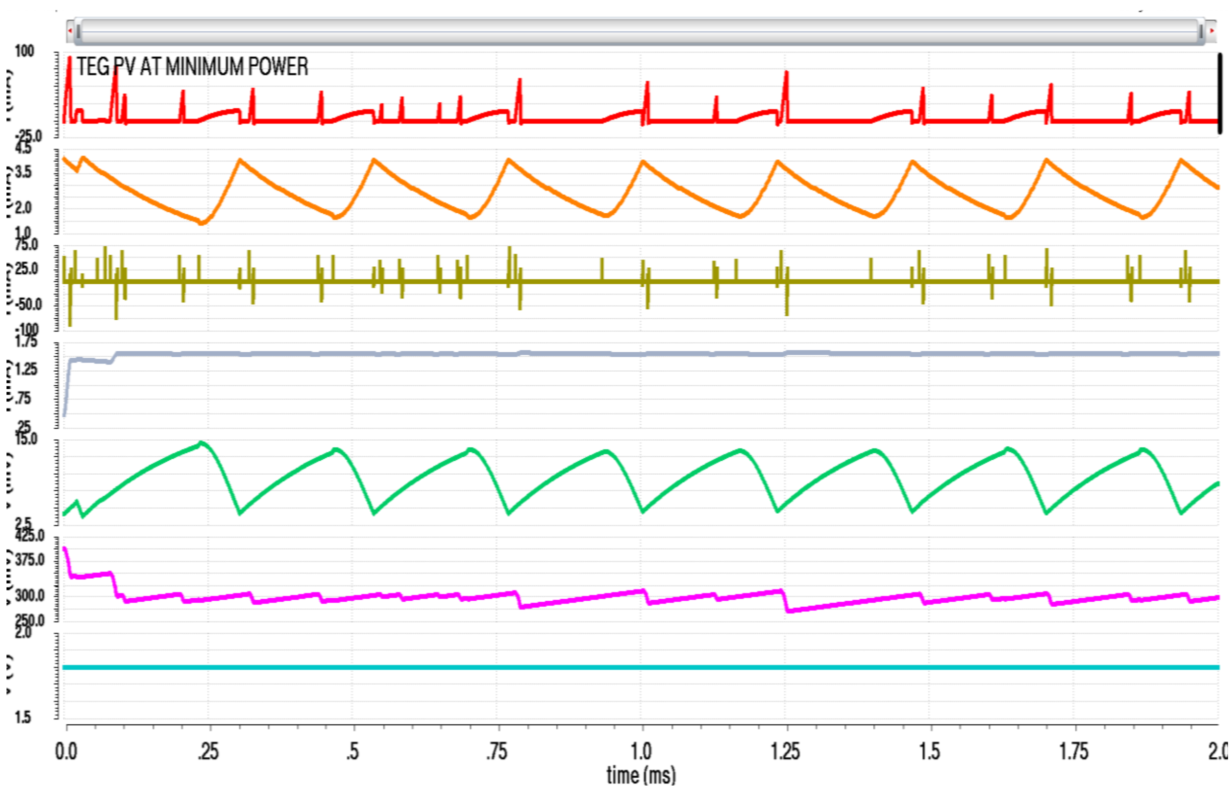


Figure 4.5: TEG and PV both supplying minimum power

4.1.6 Both TEG and PV sources supply maximum power to the system

TEG and PV source has mmaximum power to supply to the system. It can be seen clearly that PV is at MPP till the time it supplies power to the system.The load being charged to 1.8V can also be seen from the graph.

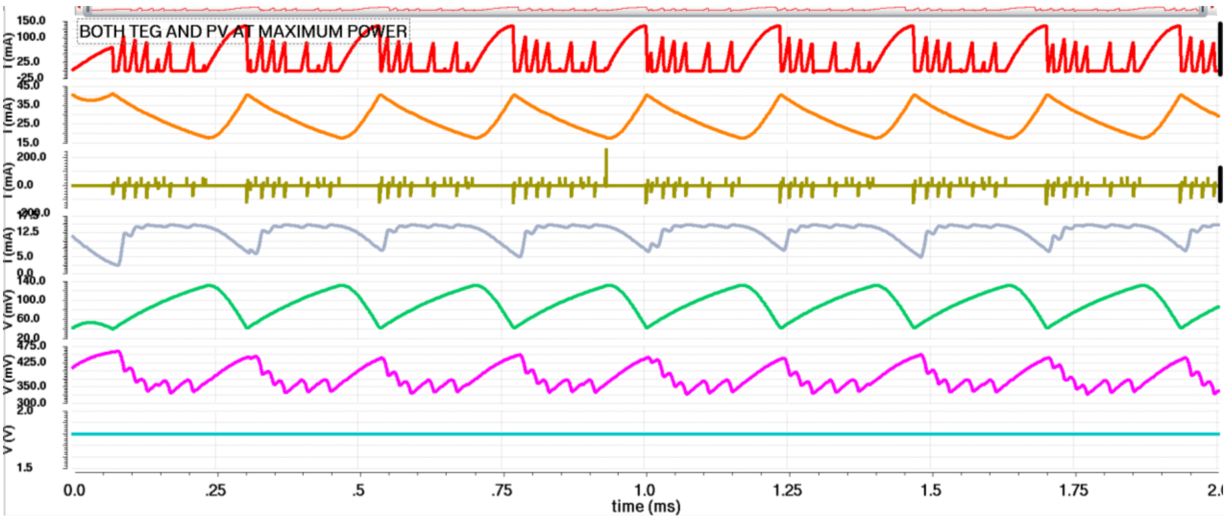


Figure 4.6: TEG and PV both supplying maximum power

4.1.7 Both TEG and PV sources supply power to the system and LDO is integrated as Load to the system

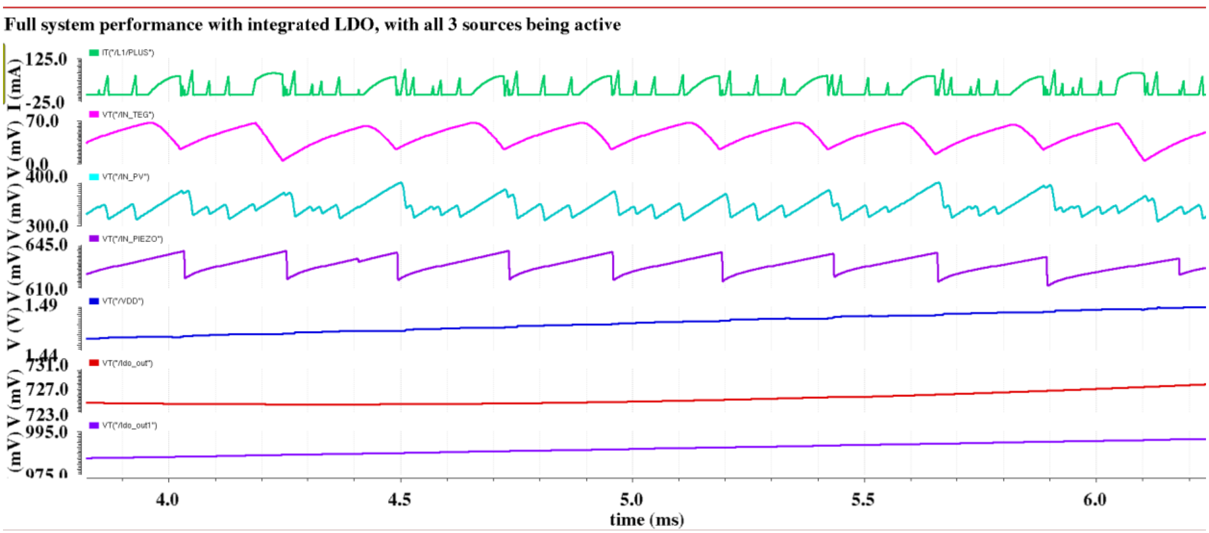


Figure 4.7: Both TEG and PV are Active and LDO is integrated as Load

4.2 System efficiency

Efficiency is one of the important parameters in determining how good the designed system is working. In the designed hybrid system, system will work in many modes depending on the availability of input sources. Efficiency of the system for different cases has been calculated and the information has been mentioned in the form of tables.

4.2.1 TEG source with a single input voltage of 20mV while PV doesn't supply power

Table 4.1: Single TEG input: 20mV; Solar: 0

Parameter	**Value**
TEG voltage	20mV
Solar	0A
Average input voltage	8.77mV
Average inductor current	2.7mA
Average input power	23.68uW
Average output voltage	1.8V
Average output current	6.3uA
Average output power	11.34uW
Efficiency	47.88 %

4.2.2 TEG with a single input voltage of 200mV while PV doesn't supply power

Table 4.2: Single TEG input: 200mV; Solar: 0

Parameter	Value
TEG voltage	200mV
Solar Current	0A
Average input voltage	188 mV
Average inductor current	13.56mA
Average input power	2.55mW
Average output voltage	1.8V
Average output current	785.5uA
Average output power	1.414mW
Efficiency	55.45 %

4.2.3 TEG doesn't supply power while PV supply a power

Table 4.3: Single TEG input: 0mV; PV(X=0.1)

Parameter	Value
TEG voltage	0mV
PV(X)	100m
Average input voltage	240mV
Average inductor current	2.05mA
Average input power	492uW
Average output voltage	1.8V
Average output current	0.251mA
Average output power	452 uW
Eeffi ciency	91.86 %

4.2.4 TEG doesn't supply power while PV supply Power

Table 4.4: Single TEG input: 0mV; PV(X=1)

Parameter	Value
TEG voltage	0mV
PV(X)	1
Average input voltage	348m V
Average inductor current	14.79mA
Average input power	5.146mW
Average output voltage	1.8V
Average output current	2.52 mA
Average output power	4.535 mW
Eeffi ciency	88.126 %

Only TEG available

Table 4.5: Different TEG inputs

TEG	Pout In (uW)	Pin In (uW)	Efficiency
20mV	11.34	23.68	47.88851
50mV	71.81	160	44.88125
100mV	354.2	639.4	55.39568
200mV	1414	2550	55.45098

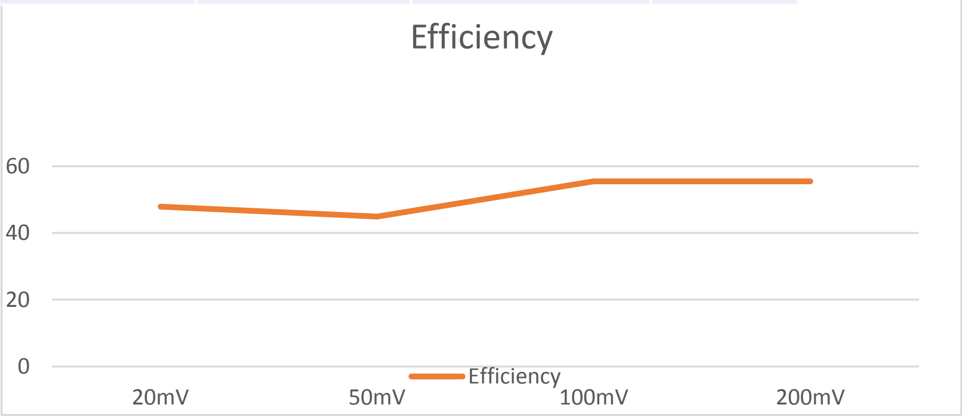


Figure 4.8: TEG Efficiency Graph

Only PV available

Table 4.6: Different PV inputs

PV(X)	Pout In (mW)	Pin In (mW)	Efficiency
0.1	0.452	0.492	91.8699187
0.4	1.8	2.03	88.66995074
0.7	3.179	3.567	89.12251191
1	4.535	5.146	88.12670035

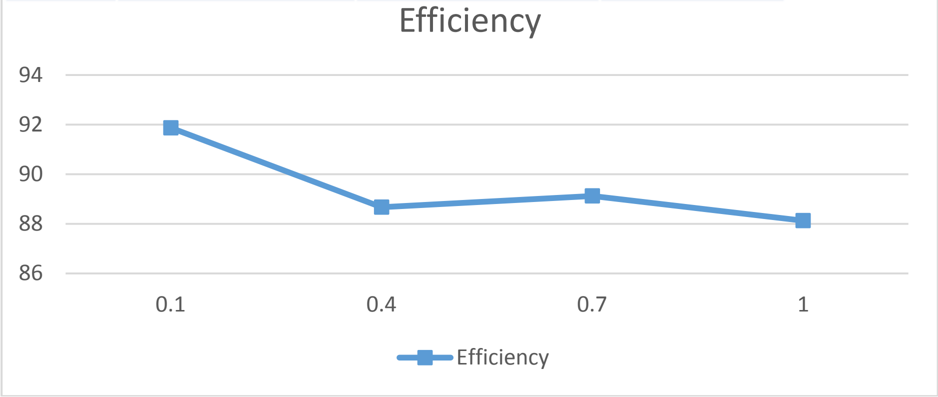


Figure 4.9: PV Efficiency Graph

All 2 sources available

Table 4.7: Single TEG input: 200mV; PV(X=1)

Parameter	Value
TEG voltage	200mV
PV(X)	1
Average input Solar voltage	381.3m V
Average input Solar Current	12.57 m A
Average input Solar Power	4.792 m W
Average input thermal voltage	91.51 m V
Average input thermal Current	3.125mA.
Average input Thermal Power	2.546m W
Average inductor current	39.58mA
Average input power	7.338mW
Average output voltage	1.8V
Average output current	3.125 mA
Average output power	5.625 mW
Eeffi ciency	76.65 %

Table 4.8: Single TEG input: 20mV; PV(X=0.1)

Parameter	Value
TEG voltage	20mV
PV(X)	100m
Average input Solar voltage	299m V
Average input Solar Current	1.545 m A
Average input Solar Power	462.1 u W
Average input thermal voltage	9.468 m V
Average input thermal Current	2.7 mA.
Average input Thermal Power	25.57u W
Average inductor current	4.63 mA
Average input power	793.055 uW
Average output voltage	1.8V
Average output current	317.2 uA
Average output power	571 uW
Eeffi ciency	72.05 %

From the above tables it can be inferred that the system has a maximum efficiency of 76.65 % when both TEG and PV work in maximum power conditions. Lesser efficiency of the system in other cases is due to power converter losses and high consumption of power in digital controller block. Efficiency can be improved by optimizing the design of power converter for switching and conduction losses, clocking the comparators and other methods. These improvements in the system are the future works to be done.

Comparisons from previous works for hybrid energy systems with the designed system can be seen from the comparison table. A peak efficiency of 76.65 % has been attained from the designed hybrid energy system.

Reference	8	10	9	11	1	This work
inputs	Photovoltaic, thermal, vibration	Thermal, solar	Thermal , piezo	Thermal,vibration,RF,solar	Photovoltaic, battery	Thermal, Photovoltaic
input range	20mV-0.16V: thermal 0.15-0.75V : solar 1.5-5V : piezo	380lux – 1010lux: solar 5K-10K-temp diff: thermal	4v-(-2v) : thermal	0.7-5V	0-40uW(0-4.8V)-PV cell 130uAH-battery	20mV-200mV : thermal 0.36V-.47V :Solar
Peak efficiency	83%	94%	66%	89.6%	93%	76.65%
MPP	yes	yes	no	yes	yes	yes
Technology node	0.35um	Using discrete board	0.8um smart power SOI	0.35um-BCD	0.5um	0.18um
Power converter	Buck-boost	boost	Rectifier+LDO	Buck-boost	Buck-boost	boost
Power consumption	NA	135uW	NA	NA	15mW	7uA for 1.8V
year	*Ieee journal of solid-state circuits* -2012	Transactions on industrial electronics-2011	Transactions on power electrnics-2015	Transactions on power electrnics-2015	*ISSCC*-2015	

Figure 4.10: Literature review of hybrid energy harvesting systems

Chapter 5

Conclusion

Present hybrid system need many modifications to be done so as to improve parameters such as efficiency, power consumption of the system, Improvements for the present system are presented down as future works.

5.1 Future works

1. The inductor current is getting saturated for the maximum TEG voltage because of low switching frequency (4 KHz-parallel connection) the charging time for inductor is high causing inductor saturation

2. Start-up circuit need to be added

3. Single PV and TEG sources can be replaced by a PV and TEG array having multiple sources so as to increase the input power

4. System can be extended to support multiple loads

5. Efficiency improvement techniques need to be adopted.

a) Finding optimum operating point for the converter

b) Optimal switch sizing

c) Power gating of required modules

d) Reduced switch losses by bias control

References

[1] H. J. Chen, Y. H. Wang, P. C. Huang and T. H. Kuo, "20.9 An energy-recycling three-switch single-inductor dual-input buck/boost DC-DC converter with 93% peak conversion efficiency and $0.5mm^2$ active area for light energy harvesting," *2015 IEEE International Solid-State Circuits Conference - (ISSCC) Digest of Technical Papers*, San Francisco, CA, 2015, pp. 1-3. doi: 10.1109/ISSCC.2015.7063082

[2] M. Ferrari et al., "Piezoelectric multi frequency energy converter for power harvesting in autonomous microsystems," Sens. Actuators A, Phys., vol. 142, no. 1, pp. 329–335, 2008.

[3] Ramadass, Y.K.; Chandrakasan, A.P., "A Battery-Less Thermoelectric Energy Harvesting Interface Circuit With 35 mV Startup Voltage," in Solid-State Circuits, IEEE Journal of , vol.46, no.1, pp.333-341, Jan. 2011

[5] J. Sankman and D. Ma, "A 12-uw to 1.1-mw aim piezoelectric energy harvester for time varying vibrations with 450-nA iQ," IEEE Trans. Power Electron., vol. 30, no. 2, pp. 632–643, Feb. 2015.

[5] H. P. Le, C. S. Chae, K. C. Lee, S. W. Wang, G. H. Cho and G. H. Cho, "A Single-Inductor Switching DC–DC Converter With Five Outputs and Ordered Power-Distributive Control," in *IEEE Journal of Solid-State Circuits*, vol. 42, no. 12, pp. 2706-2714, Dec. 2007.

[6] D.Ma, W.-H ki ,and C.-Y Tsui, "Single-inductor multiple-output switching converters with time-multiplexing control in discontinuous conduction mode ," *IEEE Journal of Solid-State Circuits*, vol. 38, no. 1, pp. 89-100, Jan. 2003

[7] S. Bandyopadhyay and A. P. Chandrakasan, "Platform Architecture for Solar, Thermal, and Vibration Energy Combining With MPPT and Single Inductor," in

IEEE Journal of Solid-State Circuits, vol. 47, no. 9, pp. 2199-2215, Sept. 2012. doi: 10.1109/JSSC.2012.2197239

[8] Claude Vankecke et al.," Multisource and Battery-Free Energy Harvesting Architecture for Aeronautics Applications", *IEEE TRANSACTIONS ON POWER ELECTRONICS*, VOL. 30, NO. 6, JUNE 2015

[9] Yen Kheng Tan et al.," Energy Harvesting From Hybrid Indoor Ambient Light and Thermal Energy Sources for Enhanced Performance of Wireless Sensor Nodes", *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS*, VOL. 58, NO. 9, SEPTEMBER 2011

[10] Michele Dini et al.," A Nano current Power Management IC for Multiple Heterogeneous Energy Harvesting Sources", *IEEE TRANSACTIONS ON POWER ELECTRONICS*, VOL. 30, NO. 10, OCTOBER 2015

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