STUDY OF THE CHALLENGES IN THE INTEGRATION OF MULTIPLE HARVESTED ENERGY SOURCES IN INTEGRATED CIRCUIT

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A project report submitted in partial fulfilment of the requirements for the award of Master of Engineering (Electronic System)

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

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ABSTRACT

Harvesting energy from the environment is being considered as a viable option to replace the current power supplies for energy constrained embedded system. With the few limitations such as a low amount of power generated using the power harvesters, the researchers are working towards generating new methods. This paper presents fully on the power converter IC for energy harvesting from multiple energy sources such as solar and ambient vibration.Design of DC–DC converter for energy harvesting from the multiple energy source is a challenging task. Multi- Input-Single-output converters provide flexibility in terms of the choice and the availability of power source, as well as enhancement in system reliability. The comprehensive operating principle, theoretical analysis and results are discussed in this paper. The designed converter has the advantages of simple configuration, fewer components, high conversion ratio and high efficiency. Inputs and output are related mathematically in terms of L, C and the duty cycle of the MOSFETs power switches. Also discussed is the derivation of the employed inductor L and the capacitor C in terms of size for a particular application.Two different type multi-input DC-DC converter are proposed by usingsolar and vibrational energy input sources and to supply the regulated output voltage for the load from the power sources. Multi-Input Converter (MIC) can deliver power from all of the input sources to the load either individually or simultaneously. MICs reduce the system size and cost by reducing the number of components. Based on the two different type of DC-DC boost converter discussed, we manage to make a choice of which converter design to use that will provide higher output voltage with lower count of passive & active components.We compared with the number of components required to build the DC-DC boost converter which design 1 was the best choice which would greatly reduce the cost and system size.

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LIST OF SYMBOLS / ABBREVIATIONS

ρ	density kg/m^3
U	potential energy
q	charge
C	capacitance/capacitor
V	potential difference/voltage
u	energy density
E	electrical field
m	milli
W	power
s	seconds
cm	centimetre
$^\circ$C	degree Celsius
D	duty cycle
T_{ON}	on period of switch
T	total period
L	inductor
ε_0	electric constant ($8.85 \times 10^{-12}\ C^2/Nm^2$)
MISO	multi input single output
DC	direct current

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Energy harvesting methodology and usage has been widely used for years and there are many technology advancements in energy harvesting. One good example of technology advancements of energy harvesting is Piezoelectricity which was createdby Curie bothers in 1880(Qi et al., 2011).

First and foremost, we are grateful to Moore's law that indicates the transistor used in integrated circuit would double foldevery18 months. Higher count of transistors will result in greater processing power and smaller ICs. Small IC's have contributed to more power efficient small devices.Many researches hard work has been lately focused towards low power, low profile, self-sustainable, and energy efficient directing to harvest solar and thermal energy as well as ambient energy from vibration. A sole source of energy harvesting is random, unbalanced and inadequate hence the efficiency is low. Combination of multiple energy sources is possible to rise the system dependability and high efficiency is achieved. Usage of low power consumption of the component(Shi et al., 2011)s, the energy harvesting efficiency is maximized.

To manage multiple energy transducers, multiple power converters are used, but, results in bigger number of components required.Passive components, such as inductors, will affect on the cost and the volume of the system.A complete multi input converter greatly reducescost due to the lower count of components and the system size.In future, these ICs can potentially be interfaced with power hungry receivers such as RFID sensor transponders or any battery-less wireless systems. RFID sensor transponders with multiple energy-harvesting sources can provide continuous sensing capabilities for a long period of time, longer reading range and data integrity even in harsh and rugged environment. It will be suitable for infrastructure and object monitoring, automatic product tamper detection, identification of harmful agents and biomedical devices for non-invasive monitoring.

1.2 Problem Statement

Energy harvesting have many advantages to offer but it has a catch.With this implementation/study of energy harvesting, there are couple of challenges(Ku et al., 2016) to be encountered. One prominent and important to all challenge is the cost for the process implementation.

One more challenge is when there's no availability of ambient energy to harvest. For instance, solar energy in dark environment doesn't contribute anything, and piezo energy needsmotion at a certain degree, and to match natural frequency of the vibration it is to be tuned. Same goes to small amount or no energy is harvested if there is no movement from the train.

For system consistency and functionality enhancement, harvesting multiple energy source is preferred(Dini et al., 2015). For instance, harvesting ambient light energy is a dominant approach. However, the frail amount of lighting bounds available energy in biomedical applications or indoor industrial. The issue is worse when the light is available for short period of time. Another alternative energy sourceis required for dependable operation. A vibration energy source that harvest energy from piezoelectric materials can be considered as one option. Combination of more power course in a power system enables it to achieve higher availability. Converters in parallel configurationis used to combineone and more energy sources to a power system. Usage of multiple power converters will require large number of semiconductor components(Sridhar et al., 2017).High count of passive components will cause cost and system size increase.

This paper willreview the challenges of integrating multiple energy power sources in term of cost and size. Also, the paper will discuss how indifference in IC circuit design with different number of components will affect volume and cost of the system.

1.3 Aims and Objectives

The aim and objective of this study is as below:

1. To study and analysedifferent type of multi input DC-DC boost converter suitable to perform integration of harvested energy from solar and vibrational energy power sources based on selected transducer for solar & vibration energy harvesting.

2. To provide suggestion of which boost converter design to use based on lower count of active & passive component that will greatly reduce cost and size.

1.4 Scope and Limitation of the Study

This will discuss how indifference in IC circuit design in this case is power converters with different number of components will affect volume and cost of the system.

In term of limitation would be sufficient time to carry out detailed experiment and venture more into more challenges in order to obtain a more beneficiary circuit design for multiple energy harvesting.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This literature review will be arranged in the order of energy harvesting approach followed by the power converters. The first few topics will be discussed about the fundamental of energy harvesting and the types of energy that will be harvested together with their expected energy density. Their energy characteristics is also tabulated together with its energy density. Moving on, integration of these multiple energy sources using power converters will be discussed. The basic operation of a DC-DC converter is explained and with that the literature review on types of power converters was done. Comparison of multiple type of converters are done as well on the criteria being decided. Last but not the least, the challenges of integrating multiple energy using power converter is discussed.

2.2 Energy Harvesting Overview

The definition of energy harvesting is the method of deriving energy from ambient energy, captured, and kept for small electronic devices application. In addition, energy scavenging is the method of mining energy from encompassing environment, the accessible surrounding vitality sources are wind, solar, piezo, RF/EM, thermal, etc. A single source of vitality gathering is irregular, sporadic and inadequate so that its productivity is low(Soavi et al., 2016). By combining energy from different sources, it is practical to extend the overall framework unwavering quality and efficiency. Multiple input energy modules combine energy from sun powered, thermal, RF/EM radiation and vibration source. More detailed breakdown of energy gathering is clarified within the following next section.

2.2.1 Energy

Energy is the basic rule of Physics and is utilized to describe the scalar quantity that's relate to an object (Beeby and White, 2010).Scalar means in the sense of having magnitude without direction. Energy cannot be destroyed or banished as per the universe law of conservation of energy. It can only be transferred or changed into different energy state. It is also famously known for its formula of Work = Force x Distance, meaning the energy of object B will be affected by object A, without any contact(Kim et al., 2014) This capability of performing a work variesin numerous way and some of them are inexhaustible relative to the environment. Potential & kinetic energy is the two type of energy to be studied in which potential energy is vital in understanding energy storage as discussed within the Energy Density section.

2.2.2 Harvesting

Harvesting is gathering something out of something in which this context is energy source (Ku et al., 2016).

If the two words, energy & harvesting are to be put together it will mean the process of gathering multiple energy source from the ambient energy and converting into a power source to a functioning electronics application.

Energy density is one of the important fundamentals to be studied for energy harvesting. Energy density is the rate of scalar magnitude against the variation in volume. Given by the formulation:

$$\rho = \frac{\Delta(\text{magnitude of scalar})}{\Delta v} \qquad (2.1)$$

The scalar measure can be mass (unit is kg/m3) (Nwogu, 2015), charge (unit is C/m3) or work (unit is Joules/m3) in the case of power. Creation of this equationwill formulatethe energy density E_ρ (also denoted by u). Potential energy per unit volume is called energy density.

The potential energy is exerted through charging of the capacitor (Davut et al., 2017)as computed as below:

$$\text{Potential energy (U)} = \frac{q^2}{2C} = \frac{1}{2}CV^2 \qquad (2.2)$$

Refer to the formula above, V is potential difference q = charge & C = capacitance. Energy density can be computed as below:

$$u = \frac{1}{2}\varepsilon_0 E^2 \qquad (2.3)$$

ε_0 is the electric constant ($8.85\ \times 10^{-12}\ C^2/Nm^2$) & E is the scale of the electrical field (Nwogu, 2015). One of the vital metrics on how much energy is accessible is known as energy density.

2.3 Energy Harvesting Sources

Most commonly known type of energy is as below:

- Mechanical (Piezoelectric energy)
- Radiated energy (Solar, light, EM/RF energy)
- Thermal energy (heat)
- Wind energy

Table 2.1 shows the advantage and disadvantage of respective energy sources during each energy source harvesting. The typical application for respective energy source is also shown in Table 2.2.

Table 2.1: Advantage& Disadvantage of Different Energy Sources(Dini et al., 2015)

Energy Source	Solar Energy	Thermal Energy	RF/EM Energy	Piezoelectric Energy
Advantage	- Great amount of energy - Well-established technology	- Always accessible	- Antenna can be combined into frame - Widely obtainable source - High output currents - Long lifetime proven - Robustness	- Lightweight - Well-developed technology - Small volume
Disadvantage	- Needs large area -Noncontinuous - Relies heavily on orientation	- Needs large area - Low power - Rigid & brittle	- Distance dependent - Reliant on available RF - Low output voltages - Difficult to develop MEMs devices	- Low conversion efficiency (high volt/low amps) - Need large area - Highly variable output - Resources are expensive

Table2.2:Various energy sources, characteristic, amount of energy density & typical applications(Roundy et al., 2003).

Energy source	Types	Characteristics	Amount	Applications
Solar	Solar/Light	Uncontrollable, partially predictable	100mW/cm^2	Outdoor, wireless sensors
Illumination	Solar/Light	Partially controllable, predictable	10uW/cm^2 ~ 100uW/cm^2	Indoor, wireless sensors
Thermal	Thermoelectric	Uncontrollable, unpredictable	10uW/cm^2 ~ 1mW/cm^2	Human body. Wearable
Wind	Motion/Vibration	Uncontrollable, unpredictable	100mW at wind speed 2m/s ~ 9m/s	Outdoor, wireless sensors
Car Engine	Motion/Vibration	Controllable, predictable	30mW	Vehicle, wireless sensors
Knee bending	Motion/Vibration	Controllable, predictable	7W	Wearable devices
EM induction	Electromagnetic radiation	Controllable, predictable	High efficiency>80%	Portable devices
Ambient RF	Electromagnetic radiation	Controllable, predictable	0.2nW/cm^2 ~ 1uW/cm^2	Wireless sensors/RFID

2.3.1 Solar energy

One of the foremost well-known and radiating ambient energy is no other than the mighty sun or known as solar power, which is well researched and used across various applications (Georgiadis, 2014).

Photovoltaic cells are used to harvest the sun light radiation and converting it into electricity. For outdoor self-sustainable applications, solar power is the favourite choice of energy source during daytime. The sun light provides infinite amount of energy which can fluctuate with short duration while going into a device depending to various factors such as weather pattern, physical condition of surroundings, specific hour of the day & type of photovoltaic cells being used, so on(Qi et al., 2011). Basically, during day light a range of 100 mW/cm^2 energy can be harvested but its only drawback is during night time. Moreover, the radiation from sun is dynamic, uncontainable & partially foreseeable in a certain fixed circumstance, yet eccentric in common cases.

Meanwhile for indoor situations, any light obtained indoor can be used as the light energy source, but its power density is considerably low of solar power and rely on illumination density depending on its distance amid energy sources and energy harvesters(Xie and Cai, 2014). Usually, the expected ranges of value are from 10μW/cm^2 to 100 μW/cm^2. Harvested light energy at indoor, the typical efficiency is moderately little with an average of 8% by using commercial photovoltaic cells whereby for outdoor is at the average of 24%.

2.3.2 Thermal Energy

Thermal energy is produced by multiple phenomena and usage, in cases of intentionally but usually the heat produced from aprocess or reaction which is wasteful, from industrialization, heating systems, automobiles, in which, provide many applications for thermal energy harvesters(Leonov, 2013).

For thermoelectric generation, a circuit voltage is created based on Seebeck effect where temperature difference between two electrical conductors with distinctive materials when their intersections are in contact produces difference of voltage between both (Vullers et al., 2010).Thermoelectric characteristics & indifference of temperature of the material decides the power densities of thermoelectric and is usually low around the range of 10μW/cm2 to 1mW/cm2. One good example of these days, wearable innovations such as smart health watches, and fitness bands are becoming popular.

Thermoelectric sensors are used to detect temperature difference between human body and surroundings and create power out of it. Gadgets equipped with thermoelectric energy source relatively have long durability and solid low maintenance, but its energy transformation effectiveness is poor. At typical temperature difference of 5 ◦C, around 60μW/cm2 energy is harvested (Paradiso and Starner, 2005).

2.3.3 Radio Frequency/Electromagnetic Energy

Radio Frequency/Electromagnetic: RF/EM energy features a generally low power density compared to other ambient vitality sources(Kim et al., 2014). The implementation of a high gain antenna into the EH framework, in any case, significantly increases the sum of energy created (Qi et al., 2011).

The energy levels accessible for collection intensely depend on the quality of the transmission and the distance between the RF gatherer and the source(Kim et al., 2014). In terms of energy change effectiveness, rectifiers for ultrahigh frequency band have accomplished more than 80 percent of conversion efficiency, with an ideal load and input RF power over 20 decibel-milliwatts (dBm)(Boisseau et al., 2012). This is often much higher than the other energy transducers for ambient EH – the highest conversion efficiency of a solar cell does not surpass 50 percent. Since the accessible surrounding RF energy density within the far-field is exceptionally low (underneath 1 mW), diodes with a low threshold voltage and fast switching speed are best for ambient EH. From this perspective, Schottky diodes have been mainly used for RF EH.

2.3.4 Piezoelectric Energy

Extracting energy from mechanical movement and vibration through 3 type of methods which is electrostatic, electromagnetic & piezoelectric can produced electrical power(Ramasur and Hancke, 2012).

We will be focusing more on the piezoelectric method, whereby its power is gained by piezoelectric materials. Piezoelectric materials are very useful for harvesting vibration energy solely to its high outputpower density(Raghavendran et al., 2018). Vibration energy harvested using piezoelectric energy harvester (PEH) produces electrical power is in the range of microwattsto milliwatts.The characteristics of the vibrational energy is random and uncontrollable as shown on the table 2.2.

2.4 DC-DC Converter

A DC to DC converter (Wang et al., 2010)acts as a switching electronic circuit that changes a fixed DC voltage to another voltage level at the output. The DC to DC converters is commonly applied on DC power supply that requires switch mode regulation. Unregulated output voltage is expected from this input of converters, hence there will be fluctuation. Despite the changing of input voltage, the average voltage needs to control in these converters and to equivalent output value.

The output voltage of the DC to DC converter is regulated by the function of the pulse width, on-time of the switch, and switching frequency(George and Kulkarni, 2018). Duty ratio is used to control the output voltage and is determined by the ratio of the ON period of the switch and total period of the switching. The equation as below:

$$\text{Duty cycle D} = \frac{T_{on}}{T} \qquad (4.1)$$

2.4.1 DC-DC Boost Converter

A boost converter produces a higher DC output voltage than its DC input voltage (Tan and Panda, 2011). So, this converter is always associated as step-up regulator or converter. The basic components required for this converter is a capacitor, inductor, switch and diode. Multiple energy source like power supply from photovoltaic cell, DC generator, fuel cells, batteries are fed into the boost converter.

With the large inductor being in series with DC input voltage, the inductor acts as source of current. In order to provide energy from the inductor and to raise the output voltages, the output is turned off occasionally when its current source is in parallel with a switch. Figure 3.1 shows the DC-DC boost converter circuit diagram.

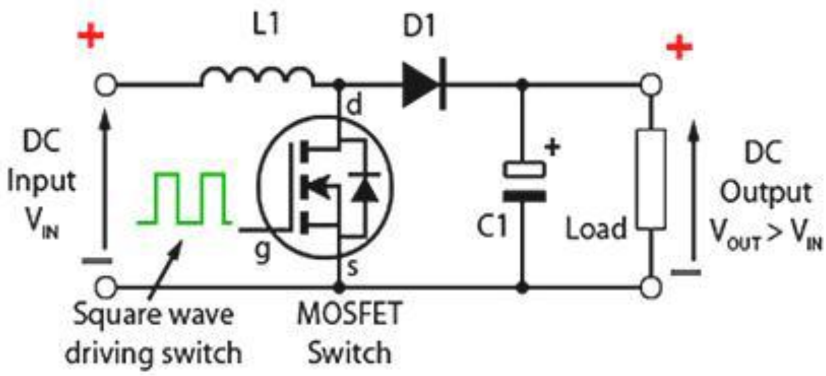


Figure 2.1: DC-DC boost converter basic circuit diagram

When the switch of the circuit is in on and off condition, the DC-DC boost converter will undergo mode of charging and discharging. Input power and output power should always be equal according to the law of conservation of energy(Khaligh et al., 2009). Therefore, in a boost converter output voltage is greater than input voltage hence output current will be lesser of the input current. So, in boost converter:

$$V_I < V_O \text{ and } I_I > I_O \qquad (4.2)$$

2.4.2 Buckboost-buckboost double input converter

Buckboost converter is a type of switch mode DC-DC converter that converts output voltage to a voltage higher or lower than its input voltage (Roundy et al., 2003). Duty cycle of the switch decides the magnitude of output voltage which is also called as step up/step down converter.

The same terminology of step up/step down transformer is used whereby the input voltage can be stepped up/down to a voltage greater than/less than its input voltage. Input power must be equivalent to output power (considering zero circuit losses) based on the law of conservation of energy(Camara et al., 2010). Input voltage is lesser than the output voltage in step-up mode, and the input current will be more than output current. Meanwhile, input voltage will be greater than output voltage during the step-down mode and input current will be lower than output current.

The methodology of buck-boost converter whereby the inductor counters sudden differences in input current. The inductor stores energy when switch is ON and when switch is opened is discharged. Large value of capacitor is used in output circuit so that the RC circuit time constant is high(Prasad et al., 2014)

In order to get a steady state constant voltage v(t) = V(constant) across the load terminals, large time constant associated to switching period is assured. The buck-boost converter is worked into two different modes(Doms et al., 2007):

1) Continuous conduction mode: inductor partly discharged before the beginning of switching cycle whereby the inductor current never goes to zero.

2) Discontinuous conduction mode: inductor is fully discharged at the end of switching cycle whereby inductor current goes to zero.

2.5 Multi input DC-DC Converter

A multi-input DC-DC converter takes multiple input energy sources whose voltage and/or power measurements are dissimilar and to obtain regulated output voltage for the load (Schupbach and Balda, 2003). It can also control power flow between each other sources and its load.

A single Multi-Input DC-DC Converter (Taghvaee et al., 2013) substitutes a few connected in parallel single converters. Source 1 to Source N can comprise of different type of energy source combinations, such as Photo-voltaic modules, thermal energy harvester, piezo harvester and Source N will be a storage unit.

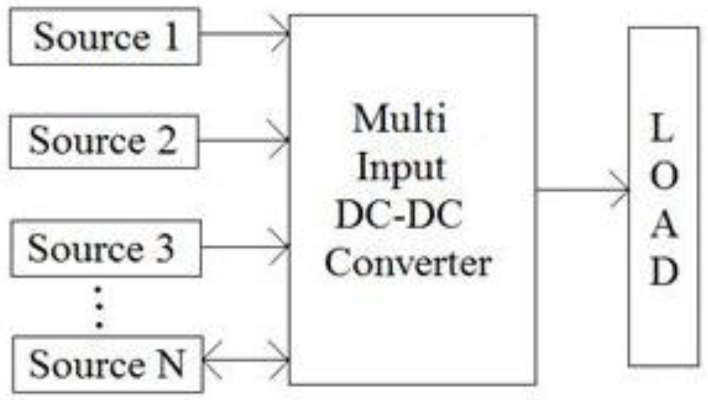


Figure2.2: Multi Input Single Output DC-DC Converter Block Diagram

2.6 Comparison of Power Converters

A multi-input DC-DC converter takes multiple input energy sources whose voltage and/or power measurements are dissimilar and to obtain regulated output voltage for the load (Schupbach and Balda, 2003). It can also control power flow between each other sources and its load.

Davide Brunelli in developed an autonomous embedded system using wind flow as an energy source. A highly efficient buck boost converter has been used for optimal power point tracking. Experimental results prove that the wind generator can operate efficiently over a wide range(Brunelli, 2016).

Gajendranath Chowdary in (Chowdary and Chatterjee, 2015) proposed an open circuit voltage-based DC-DC converter for voltage boosting to harvest energy from sub-microwatt power sources. All circuits operate in sub threshold region and an efficiency of 50% is achieved for input power levels greater than 2µW. External voltage is used for boot-strapping.

The paper in (Szarka et al., 2013) describes the power management circuitry for vibration energy harvester that generates alternating currents at low voltages. The power conditioning system is implemented using a full wave boost rectifier topology that is capable of operating at 100 input power levels. The ACDC converter utilizing the stray inductance of the harvester achieves an efficiency of 76% including quiescent losses.

The paper in (Bandyopadhyay et al., 2014)describes Nano-Watt boost converter for a wireless sensor network implemented on 0.18 CMOS process. An end cochlear potential is used to harvest energy, and this is used as input by the boost converter. The peak conversion efficiency of the boost converter is 56% and the quiescent current is 544 pW. The quiescent current is minimized using a charge pump and ultra-low power VLSI circuits.

Power converters are essential for energy harvesting systems to dissipate controlled output voltage to other devices in the system (El-Damak and Chandrakasan, 2016). Also, the efficiency of power management circuit depends on the dc – dc converter used for supply voltage scaling. Table 2.3 summarizes and compares different topology of power converters, their efficiencies at ultra-low power and the quiescent power.

Table2.3: Performance summary and comparison of power converters

	(Chen et al., 2011)	(Kadirvel et al., 2012)	(Instruments, 2013)	(Jung et al., 2014)	(Bandyopadhyay et al., 2014)	(El-Damak and Chandrakasan, 2016)
Topology	Switched capacitor with charge pump (boost)	Inductive boost	Inductive buck	Switched capacitor	Inductive boost	Reconfigurable inductive buck/boost
Input voltage	450mV	80mV – 3V	2-5.5V	0.14V – 0.5V	20mV-70mV	0.14-0.62V
Output voltage	3.6V	2.2-5.25V	1.3-5V	2.2-5.2V	1.5V-1.9V	2.9-4.1V
Output power	10nW-160nW	1uW-80mW	2.5uW-130mW	5nW-5uW	544pW-4nW	10nw-1uw
Efficiency at ultra-low power	35%	38%	55%	50%	53%	80%
Quiescent power	7.3nW	957nW	760nW	<3nW	544pW	3.2nW

A non-isolated DC/DC converter is proposed in (Yalamanchili and Ferdowsi, 2005)by combining the buck and buck-boost converter a dual input DC/DC converter containing sources with different voltage levels is analysed. Furthermore, operational modes are defined keeping in consideration the input source availability as well as conduction states of switches associated with them. However, the reduced efficiency of the design is further enhanced by reducing the switching losses in (Chen, 2006).

Dobbs BG and Chapman PL (Dobbs, 2003) proposed a buckboost topology-based converter with n-numbered inputs. Although number of components are reduced yet the cost and size are high because a transformer is required to reverse the negative reference output. In addition to this simultaneous delivery of power is also not possible.

Later in (Dobbs, 2003) the authors modified the design by a bidirectional multi input DC/DC converter. However, it used more number of switches due to which it suffers from more conduction losses. The boost converter proposed in (Marchesoni,2007)greatly reduced the conduction losses of switches. However, the efficiency can be further increased by reducing the diode reverse recovery current as mentioned in (Wai R,2011).

Like (Wai R,2011) another Zero Voltage Switching multi input converter is proposed in (Marchesoni,2007) with high efficiency and reduced losses and switches count is investigated.Integrated converter topologies are presented in (Yalamanchili and Ferdowsi, 2005)like Integrated buck boost-buck boost are also presented but again with limitations of no simultaneous supply to the load.

Various multi input boost converter topologies were proposed for integrated energy system. However, some of them could not supply power simultaneously (Nahavandi, 2014) while others do not have efficient battery charging/discharging strategy (Shao, 2014).

Although there are few isolated converters which can be used for low voltage and low power applications, such as flyback and forward converters, however non-isolated are still more preferable. As far as other isolated converters are concerned, such as full bridge and half bridge converters, they are suitable for medium to high voltage applications (Chen, 2002).

In (Wang, 2004) a family of a multi-port bi-directional isolated DC/DC converters is discussed in great detail. However, converter with less component count, simple design, low cost and high efficiency (Chiu, 2005) are always favoured whether it is a non-isolated or isolated converter. By utilizing soft switching technique to deliver power individually and simultaneously, a full bridge converter is proposed in (Yang, 2009). This also makes the topology design simpler by reducing the switches and consequently switching losses.

Authors in (Wai R,2009) used active clamping circuit in a bidirectional dual input current source type isolated converter and achieved the benefits like soft switching, high efficiency, isolation between input and output etc. As compared to the multi input full bridge converters, a bi-directional DC/DC converter having three half bridges can provide power delivery in either directions with higher efficiency or reduced component count (Wu, 2011).

By integrating half bridge and forward flyback converter and synchronous rectifiers, three-port half bridge converters can also be designed which have several advantages in addition to the lighter weight see for example (Wu, 2011).

Table2.4: Multi-input DC/DC converter topologies comparison

Topology	Cost	Reliability	Flexibility	Modularity potential	Efficiency
MI buck	++	++	+	+	+++
MI boost	+++	++	+++	++	++++
MI buck-boost	+	+	++	+	+

Table 2.4 shows multi-input DC/DC converter comparison in term of cost, reliability, flexibility, modularity potential and efficiency. The more number of '+' sign indicates that it is better than others for example '++++' is better than '+++' and so on. Similarly, '+' sign also indicates that it is better than '-' which is better than '--' and '- - -'.

2.7 Multiple Energy Harvesting Challenges & Limitation

Numerous benefits, which increase system performance, can be obtained at the same time with the use of multi-source within the energy harvesting frameworks. Utilizing numerous energy sources gives energy diversity gain to the energy harvesting system(Ou et al., 2009).

The cost of a multi input converter can be generally estimated based on the number of components being used in the particular topology. It can be easily observed, by comparing the single input converters with multi input converters that the cost reduction is achieved in multi input converters by maximizing the usage of the common components and thus a reduced number of components are needed.

Because common componentsare shared. Therefore, as the number of common components increases the cost decreases. For example, if the output filter capacitor is the only
common component then it will help to achieve only a few cost savings. Because isolated converters require transformer for input-output isolation they tend to be more costly and bulkier than non-isolated converters. However, in non-isolated topologies, boost converters, due to reduced component count, are cheaper than buck converter.

In (Xiao, 2007) photovoltaic (PV) applications are found to have more benefits, amongst the non-isolated DC/DC converters, from boost converter rather than buck converter. Similarly, multi input isolated full bridge converters have high cost due to bulky transformer as well as large number of switches therefore they are also not preferable in PV renewable energy systems

The flexibility of multi input converter means how well the topology can handle the integration of different input sources and provide wide output voltage ranges. Becausethe main goal of any multi input converter is to provide desired output voltage by integrating several input sources therefore in these converters the input interface ishighly considered. Among the non-isolated converters, the Cuk and SEPIC converters have an edge over other because they can step-up/step-down the input voltage and provide ripple free and continuous input currents. The isolated half bridge converters have more flexibility than full bridge converters. This indicates that the presence oftransformer in any converter is also beneficial because they may provide a large voltage ratio.

Multiple-input DC–DC boost converters are reasonable system for energy gathering from numerous small-power sources, since of low component count and space necessity and accomplishment of maximum power extraction(Shi et al., 2011). A multi-input DC to DC boost converter to pull the power from numerous low power energy gathering sources is projected in this paper.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Integration of Multiple Energy Source

Due to different energy profile over time, we need to determine which energy is able to sustain during the entire process of energy harvesting. The basic block diagram of energy harvesting is usually each energy source will be connected to one converter and then to a load. So, introduction of multi input DC-DC converter, will greatly help to combine more than 1 energy source and provide a stable output.

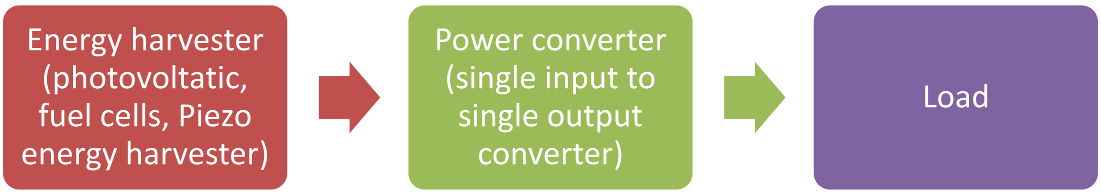


Figure 3.1: Basic block diagram of energy harvesting

In this paper we will use the transducer as shown in Table3.1 and based on the harvested power we will be choosing the solar energy as well as the vibrational energy.

Due to the in availability of solar energy during the day, we will be able to use the vibrational energy during the night. The reason to choose solar and vibrational energy due to their characteristic of energy source whereby solar has unpredictable and uncontrollable source meanwhile vibrational energy has predictable and controllable source. The reason of choosing solar and vibrational energy source is to provide continuous flow of energy source when one energy source is lacking in during certain period of time.

Table 3.1: Indicative harvested power values from different transducer types.

Energy source	Harvested power	Conditions / Available power
Light / solar	60mW.	6.3cm x 3.8 cm flexible a-Si solar cell. (Niotaki, 2014)
Kinetic / Vibration	8.4mW	Piezoelectric shoe mounted(Shenck, 2001)
Thermal	0.52mW	Thermoelectric generator (TEG) (Georgiadis, 2014)
Electromagnetic	0.0015mW	Ambient power density 0.15 uW/cm2 (Georgiadis, 2010)

With integration of multiple energy from different source of energyusing multi input DC-DC converter, whereby in this paper we are focusing on solar and vibration energy. The output voltage from DC to DC converter is obtain by the regulation of the converter. This paper we will design two different type of DC-DC converters using the MULTISIM software to compare its output voltage. Moreover, during the design of that two different DC-DC converter, number of semiconductor component is considered as well.

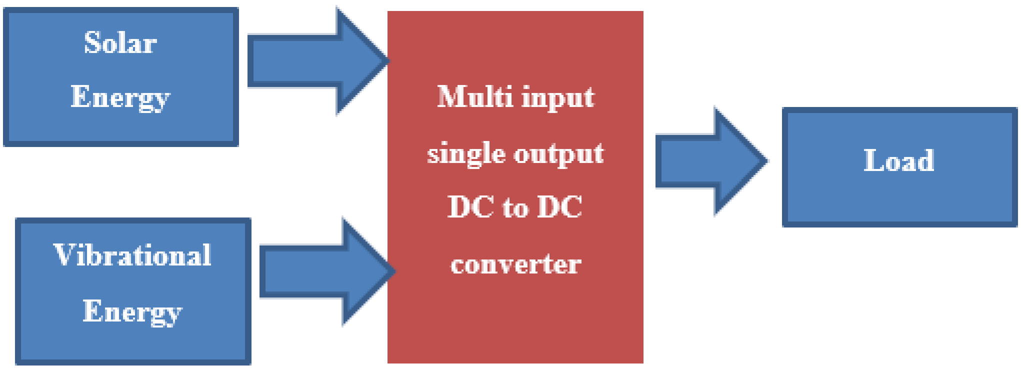


Figure 3.2: Block diagram of multiple energy harvesting

Below are shown the schematic circuit of the two different type of boost converter to be designed and compared to measure its performance and advantage of each other using the Multisim software. A multi-input single output DC to DC boost converterdesign 1 is shown in figure 3.3 whereby figure 3.4shows themulti input DC-DC boost converter design 2.

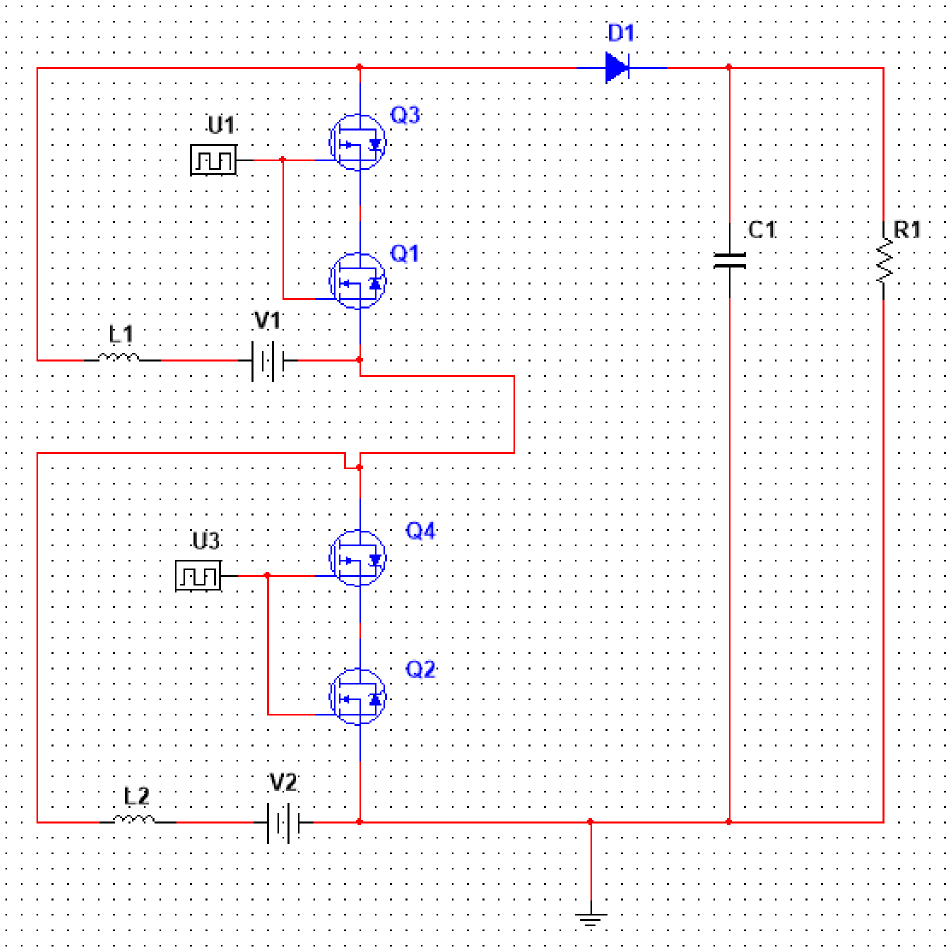


Figure 3.3: MISO DC-DC Boost Converter Design 1

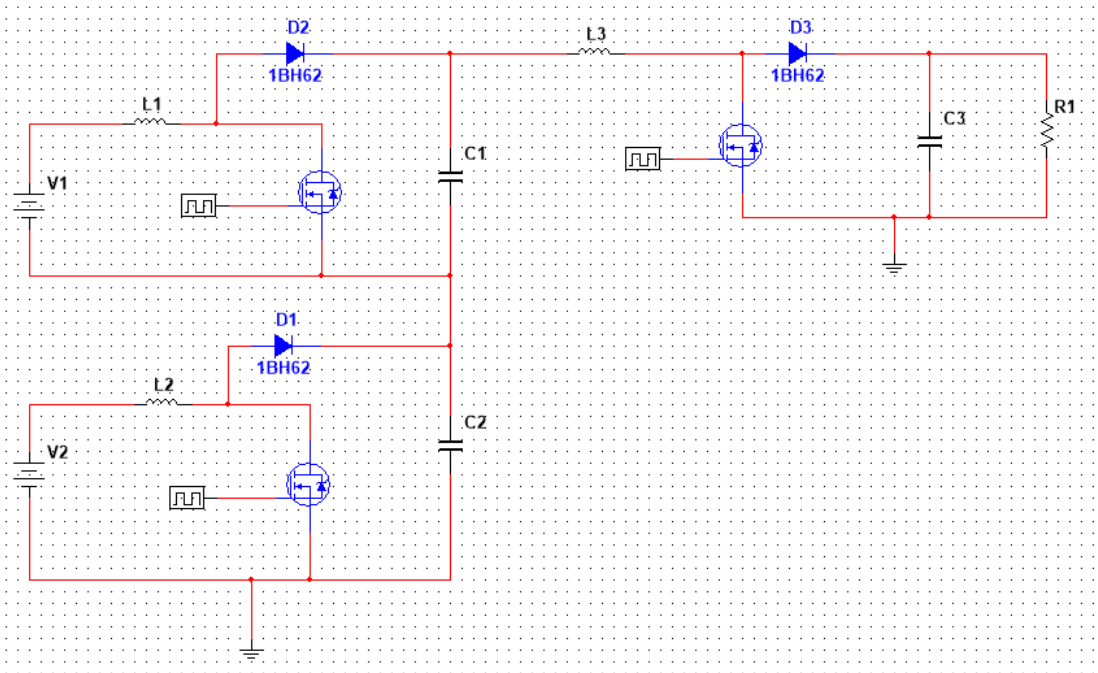


Figure 3.4: MISO DC-DC Boost Converter Design 2

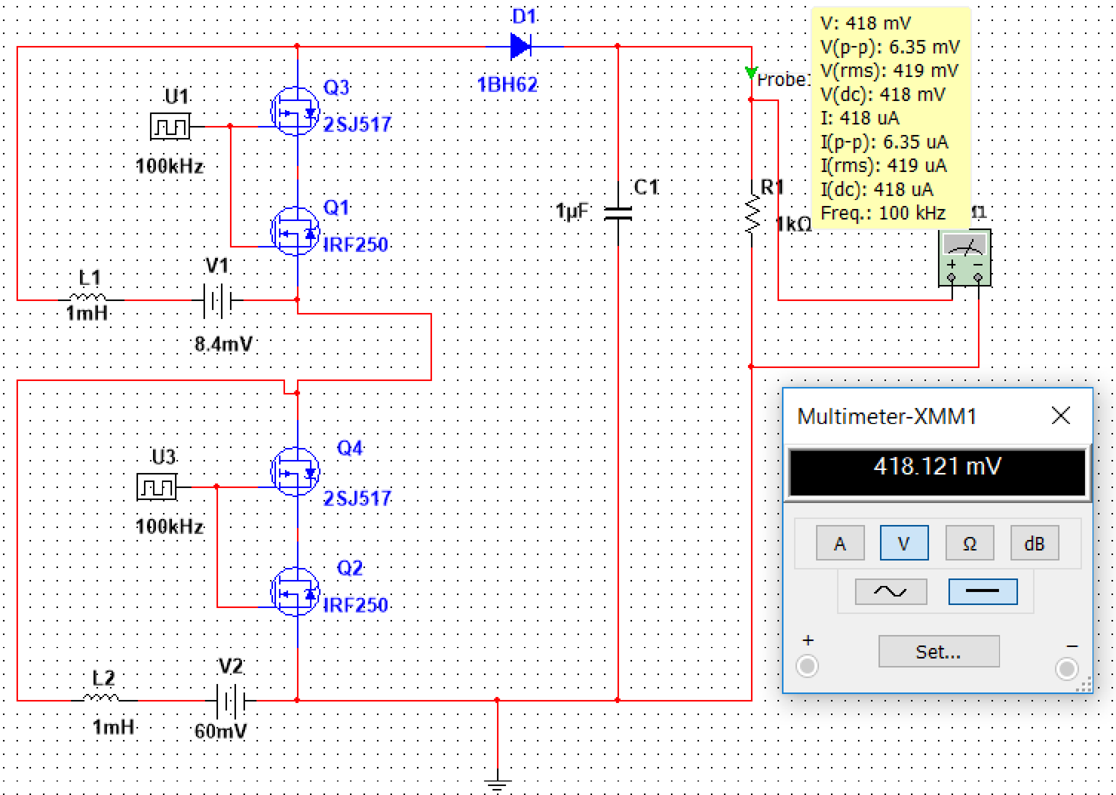
CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Design and Simulation Result

On the boost converter design 1, solar energy & vibrational energy input sources are taken for an example in this paper with its respective output designed as follow: V1 = 8.3mV(Shenck, 2001)& V2 = 60mV(Niotaki, 2014), and the switching frequency is set at 100kHz. The calculated values of the inductor and capacitor as sized as L1 = L2 = 1mH, C1 = 1uF, as shown in Fig. 4.1, also duty cycle of each MOSFET switch Q1 = Q3 = 75%& Q2 = Q4 = 50%.

The design is put into MULTISIM software with the declared parameters above and the results have shown in Fig. 4.1, where a 418mV output DC voltage is attained from V1 = 8.3mV & V2 = 60mV input DC source.



<u>Figure 4.1: Multisim simulation result DC-DC boost converter design 1</u>

Meanwhile on the comparison of the design 2 of boost converter uses the same as solar energy & vibrational energy input with its output is designed as follow: V1 = 8.3mV (Shenck, 2001)& V2 = 60mV(Niotaki, 2014), and the switching frequency is set at 100kHz. Moreover, values of inductor and capacitor are L1 = L2 = L3 = 1mH, C1 = C2 =C3 = 1uF as shown in Fig. 4.2, and duty cycle of each MOSFET switch Q1 = Q3 = 50% and Q2 = 75%.

MULTISIM software is used to simulate those mentioned parameters above and the simulation result is shown in Fig. 4.2, where a 206mV output DC voltage is attained from V1 = 8.3mV & V2 = 60mV input DC source.

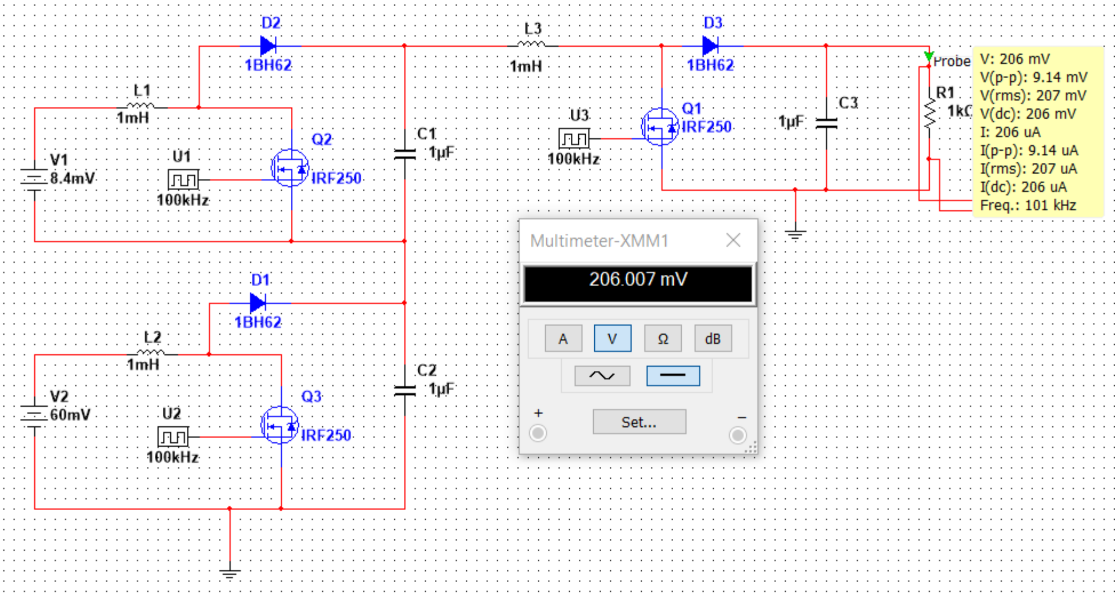


Figure 4.2: Multisim simulation result of the DC-DC boost converter design 2

Based on the simulation result tabulated below, it shows the design 1 boost converter is the better solution to use for MISO DC-DC converter as it requires a lower number of passive components as well as smaller amount of active component. Moreover design 1 of the boost converters has only 1 diode as compared to design 2 which means the size of the circuit will be smaller than design 2.Furthermore, design 1 provides more stable and higher output than design2.

Table 4.1: Comparison of two different MISO DC-DC boost converter

MISO DC-DC Converter	No. of active component	No. of passive component	Total no. of components	Output Voltage
Boost Converter Design 1	5	4	9	418mV
Boost Converter Design 2	6	7	13	206mV

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In a nut shell different type of multi-input single output boost converter that is being used for multiple energy harvesting which is solar and vibration energy has been discussed. The two different MISO DC-DC converter of boost converter is designed using the Multisim software and is verified with its output voltage.

The application of multi-input single output DC-DC converters in low voltage applications has increased the power safety and consistency, integration cost is reduced and switching losses minimized. Combination of multiple energy source is possible. With a clear understanding, if one wants to integrate two or more energy sources, the MISO DC-DC boost converter design 1 will be chosen as comparison of design 2 due its better output voltage, smaller system size due to less passive component as summarized in Table4.1. The additional advantages of design 1 converter arerather than using individual converter for respective energy source, MISO DC-DC converter will greatly reduce the system cost and size.

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