Cape Peninsula University of Technology

DEVELOPMENT OF A LOW ENERGY COOLING TECHNOLOGY FOR A MOBILE SATELLITE GROUND STATION

By

JANVIER KAMANZI

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Supervisor:Prof MTE KAHN

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DECLARATION

I, Janvier Kamanzi, declare that the contents of this thesis represent my own unaided work, and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed **Date**

ABSTRACT

The work presented in this thesis consists of the simulation of a cooling plant for a future mobile satellite ground station in order to minimize the effects of the thermal noise and to maintain comfort temperatures onboard the same station. Thermal problems encountered in mobile satellite ground stations are a source of poor quality signals and also of the premature destruction of the front end microwave amplifiers. In addition, they cause extreme discomfort to the mission operators aboard the mobile station especially in hot seasons. The main concerns of effective satellite system are the quality of the received signal and the lifespan of the front end low noise amplifier (LNA). Although the quality of the signal is affected by different sources of noise observed at various stages of a telecommunication system, thermal noise resulting from thermal agitation of electrons generated within the LNA is the predominant type. This thermal noise is the one that affects the sensitivity of the LNA and can lead to its destruction. Research indicated that this thermal noise can be minimized by using a suitable cooling system. A moveable truck was proposed as the equipment vehicle for a mobile ground station. In the process of the cooling system development, a detailed quantitative study on the effects of thermal noise on the LNA was conducted. To cool the LNA and the truck, a 2 kW solar electric vapor compression system was found the best for its compliance to the IEA standards: clean, human and environment friendly. The principal difficulty in the development of the cooling system was to design a photovoltaic topology that would ensure the solar panels were always exposed to the sun, regardless the situation of the truck. Simulation result suggested that a 3.3 kW three sided pyramid photovoltaic topology would be the most effective to supply the power to the cooling system. A battery system rated 48 V, 41.6 Ah was suggested to be charged by the PV system and then supply the power to the vapor compression system. The project was a success as the objective of this project has been met and the research questions were answered.

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- The love of my life Mercy Kileo
- My mother Maria Nyirampitiye
- My classmates
- Special thanks to our God Jehovah

DEDICATION

To my wife Mercy Kileo

GLOSSARY

AC	Air Conditioning
ADCS	Attitude Determination and Control System
C&DH	Command and Data Handling
Cal Poly	California Polytechnic University
CMOS	Complementary Metal Oxide Silicon
COP	Coefficient Of Performance
CPUT	Cape Peninsula University of Technology
DC	Direct Current
DHET	Department of Higher Education and Training
ETC	Evacuated Tube Collector
FPC	Flat Plate Collector
FSATI	French South African Institute of Technology
GEO	Geosynchronous Orbit
GPS	Global Positioning System
GUI	Graphical User Interface
GWP	Global Warming Potential
HVAC	Heat Ventilation and Air Conditioning
ICUE	Industrial and Commercial Use of Energy
IEA	International Energy Agency
LEO	Low Earth Orbit
LNA	Low Noise Amplifier
MATLAB	Matrix Laboratory

MCE	Magneto Calorific Effect
MEO	Medium Earth Orbit
MPP	Maximum Power Point
MSGS	Mobile Satellite Ground Station
NF	Noise Figure
ODP	Ozone Depletion Potential
PCM	Phase Change Material
PSIM	Power Simulator software
PV	Photovoltaic
RF	Radio Frequency
RMD	Refrigerant Metering Device
SANSA	South African National Space Agency
SBS	Sick Building Syndrome
SNR	Signal to Noise Ratio
TEC	Thermoelectric cooling
TRNSYS	Transient System
USA	United States of America
USSR	Union of the Socialist Soviet Republics

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CHAPTER ONE: PROPOSAL

1.1 Introduction

Satellites have been so implicated in humans' life in various domains such as telecommunications, weather forecast, disaster detection, global position services to name but a few. These man-made satellites, though at first they were developed as a sign of supremacy between then superpowers, have been since resorted to in various space missions. They operate with electromagnetic energies also known as signals and therefore, the satellite missions' success depends on the quality of the received signals. However, these signals are certainly corrupted by the noise and this affects the mission. The purpose of this project is to providean approach that would minimize the noise on board a satellite mobile ground station by using cooling technologies.

1.2 Research problem

Thermal problems encountered in mobile satellite ground stations are the source of the poor quality signals, and the premature destruction of the front end microwave amplifier. In addition, it is the source of the discomfort of the mission operators aboard the mobile station. In satellite communications, concerns are first and foremost about the quality of the received signal and the lifespan of the front end low noise amplifier (LNA). The quality of the signal is affected by different sources of noise that can be observed at various stages of a telecommunication system. However, the thermal noise resulting from the thermal agitation of electrons generated within the low noise amplifier (Iida, 2000:36-37) is the most predominant type of noise and affects the sensitivity of the LNA on one hand and can lead to the destruction of the LNA on the other hand. The received signals having the power below a certain level cannot be sensed whereas the signals of with the power above a certain level can lead to a premature destruction of the LNA. The thermal noise is the power measured when there is no input signal applied to the amplifier. It is directly proportional to the temperature where the amplifier is hosted (Equations 1.1 &1.2). Pozar (2005) indicated that this thermal noise can be reduced by keeping the microwave low noise amplifier in a cold environment. The LNA and all the receiving equipment commonly hosted at a ground station, which can be either static or mobile, experience the effects of thermal noise differently and the approach towards the cooling of those equipment are different depending on the type of the ground station.

Regarding a satellite mobile ground station, which is our case of study, thermal issues must be dealt with in a particular way. In fact, mobile satellite ground stations are called to operate outdoors and are likely to be exposed to harsh hot weathers. A mobile satellite ground station structure is also meant to be kept closed for the safety of the equipment constituents of the ground station and as a result, inside temperature is the subject of increase. This can affect quality of the signal and the comfort of the engineers in charge of the MSGS operation. The cooling techniques for the MSGS must also take into consideration the mobile aspect of the ground station especially with regards to the power supply.

$$V_{n(rms)} = \sqrt{4KTRB} \text{ Volts} \qquad \text{Equation (1.1)}$$

$$N_0 = KTB \text{ (Watts)} \qquad \text{Equation (1.2)}$$

(Johnson or Nyquist noise)

Where :

B : Bandwidth (Hz)

K : Boltzman constant (^{0}K)

N_0 : Thermal noise power (Watts)

R : Resistance of the circuit (Ω)

T : Temperature (^{0}K)

1.3 Background to the research problem

Since 2009, the French South African Institute of Technology (FSATI) under the umbrella of the Cape Peninsula University of Technology (CPUT), have been developing small satellites designated cubeSats (FSATI, 2010). This designation has been attributed to those small satellites of with shapes of a scalable cube of 10x10x10 cm cube and of 1kg wet mass. In this regard, FSATI has already developed a complete flight model product, ZACUBE 1. The launch process is still ongoing and the development of ZACUBE 2 is at an advanced stage. The cubeSats offer the advantage of completing the same space missions as bigger satellites at enormously lower cost and shorter development time. The common space missions whereby the satellites are called upon are communications, weather forecast, debris monitoring, disaster prevention and management, global positioning system (GPS); and in all these types of missions, a satellite is constantly in communication with the ground for data collection and mission control purposes. At FSATI, a fixed ground station is already set up and is located at the Goldfields building (Figure 1.1). However, for broad use of cubeSats, mobile ground stations are to be resorted to when it comes to the access to remote areas, to the better quality communication in broadcast and multicast and to the flexibility of operation of the ground stations.

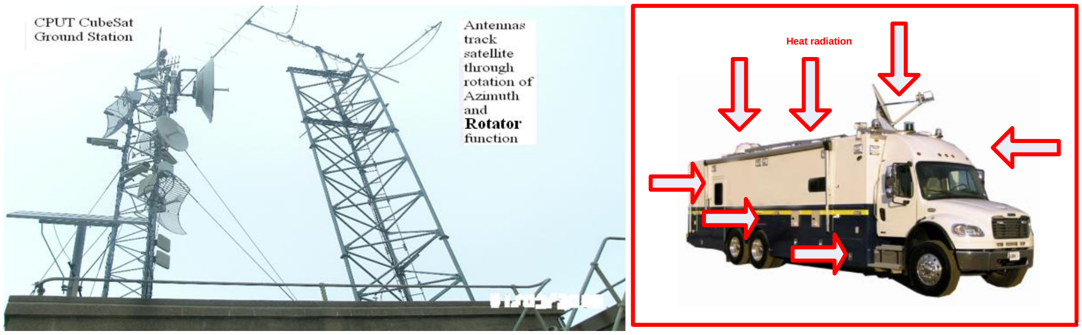


Figure 1.1: a) Fixed ground station, b) Example of a mobile ground station

1.3.1 Brief history on satellites

A satellite can be viewed as any object orbiting a planet. There are two types of satellites namely natural satellites and artificial satellites which are man-made systems. The way natural satellites orbit the planets of the solar system; artificial satellites do the same to orbit the earth in order to accomplish a specific mission. The first satellite to have ever been launched was called Sputnik1 in 1957. It was undertaken by the former Union of Soviet Socialist Republics (USSR). The successful launch of Sputnik1 has triggered the space race for various reasons. It occurred during the cold war when the USA and the USSR were in a rivalry on political, military and technological points of view. Though the satellite’s success to orbit the earth had a scientific mission related to then predicted threat from solar activity, the Americans saw it as a threat military wise; because their bitter rivals had proven the ability to launch ballistic missiles to them or to any other territory. The contest for supremacy by then super powers led to many other satellites’ launches with various missions profitable to the humanity welfare.

1.3.2 Mission concept

A mission concept can be viewed as a platform that provides the architecture and interaction of the elements involved in a space mission (Wertz, 2005:11). Behind any space mission, there is an issue or a problem that must be addressed from the space environment, the main object being the earth. Space missions are conceived in order to lift the challenges encountered in gathering data from the earth environment. Some data are gathered via a remote sensing process by using aerial sensors. The remote sensing process helps classify the objects in space and on the earth by detecting propagated signals emitted by the objects under study. Some other data are acquired through imaging process where cameras are used to take images of physical objects. Telecommunications are another application of satellites whereby a transmitting side is linked to the receiving side via a relay satellite. The mission is tailored following an architecture known as a mission concept. The mission concept describes all the essentials for the predefined goals to be achieved. The mission concept specifies the subject of the mission. The subject can be seen as the physical object under the study, it can be the earth, the atmosphere or any other object in the space environment. The mission has to be carried out using the payload on board. The payload is the component that collects the information and relays it to the ground station by radio means. The payload can be scientific sensors or optical cameras. The ground station consists of equipments and hardware that processes the information from the satellite. The ground station, that can be fixed or mobile, also ensures the control of the mission and the command and the data handling. The space section of the mission is designated as the space segment whereas the ground section is also known as the ground segment. The space segment needs a lunch element to be put on orbit. The mission can be mandated to a single satellite or to a constellation of satellites. A constellation is a set, group or collection of satellites that work together toward the mission a single satellite cannot fulfill. They can be put on a single orbit with spacing angles or to different orbits. The personnel and staff are part of the mission operation as it is shown on the Figure (1.2)

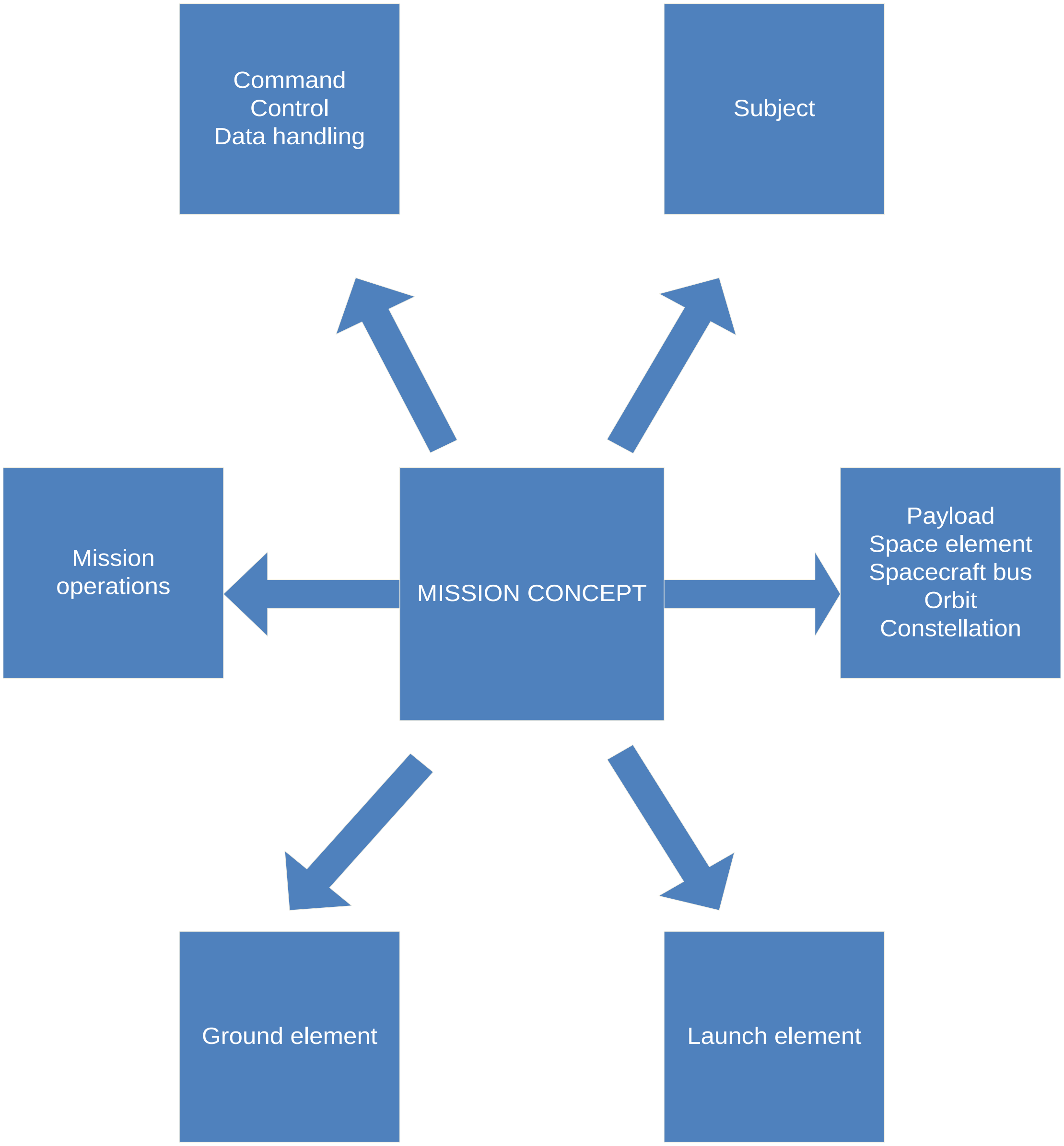


Figure 1.2: Space mission architecture (Adapted from Larson & Wertz, 2005:11)

1.3.3 CubeSat concept

CubeSats belong to the family of the man-made satellites orbiting the earth at the low earth orbit (LEO).According to California Polytechnic University (Cal Poly) standards (Puig - Suari & Twiggs, 2004), a basic for cubeSats is a 10 x 10 x 10cm - cube with 1 kg of wet mass, also known as Pico-satellite. The classification of satellites has been shown in Table 1.1 (David, n.d).

Table1.1: Satellite classifications (David, n.d)

Category	Mass range (Kg)
Large satellite	>1,000
Medium sized satellite	500-1,000
Minisatellite	100-500
Microsatellite	10-100
Nanosatellite	1-10
Picosatellite	0.1-1
Femtosatellite	<0.1

This basic unit, referred to as 1U cubeSat to mean one unit, is scalable only in one direction with its multiples so as to obtain any desired size satellite. The small size of the cubeSats implies a small area available for the solar panels and hence a small power budget. Arnold *et al.* (2012) indicate that the power budget of a 1U cubeSat ranges between 1W and 2.5W and in table 1.2; the mentioned authors give details on the power budget according to the cubeSat subsystems. The cubeSat described in the table shows that the total power of 527mW of which 276 mW are allocated to the communication system. With such small communication powers, there is an indication that the transmitted signals are likely to be small.

Table1.2: Example of the power budget for a 1U cubeSat

Subsystems	Power usage
ADCS (Sun sensor)	0
CMOS camera payload	70mW
C&DH (ARM7 Core)	110mW
Color camera payload	80mW
Communication	276mw
Total	**527W**

CubeSats are being developed worldwide by educational institutions, private firms, and governments to achievesame missions as bigger satellites. Their small mass, low development cost and reasonable development time have made cubeSats an efficient tool for space science and exploration. The cubeSats operate in LEO whereby it orbits the earth in approximately 96 minutes. However, smaller satellite systems are more vulnerable than bigger satellites when it comes to the noise in the received signal due to low powers involved in the signal transmission as shown in Table 1.2.

1.3.4 Concept of noise in satellite communications

The performance of a communication system can be assessed looking at the quality of the received signal that should be of the same quality as it was transmitted. But it happens that the signal gets corrupted along the way to the receive side. In other words, the transmitted signal has picked up some undesired electrical energy. In satellite communications, any unwanted source of energy that interferes with the transmitted signal is called noise. Noise can interfere with the signal at the transmit side, in the propagation medium, at the Radio Frequency (RF) equipments of the satellite and at the receiving side. At the transmit side, the noise power is considered to be negligible when compared to the transmitted signal. In the transmission medium (uplink and downlink), the noise depends upon the atmospheric conditions, upon the solar activity and upon the man-made noise. The man made noise in the propagation medium can emanate from the other spacecrafts that are in space. Their motors or engine activities may generate a magnetic field that can interfere with the transmitted signal on its way up to the satellite or down to the receiver. This type of noise is dealt with by the low noise amplifier (LNA) that amplifies weak signals before they are detected. The LNA ensures that the low power signal that is transmitted from a satellite located at between low earth (LEO) and geosynchronous orbit (GEO), is recovered at the receive side. A LEO is an orbit located at between 160 and 800 kilometers, whereas a GEO is an orbit approximately at 36,000 kilometers.

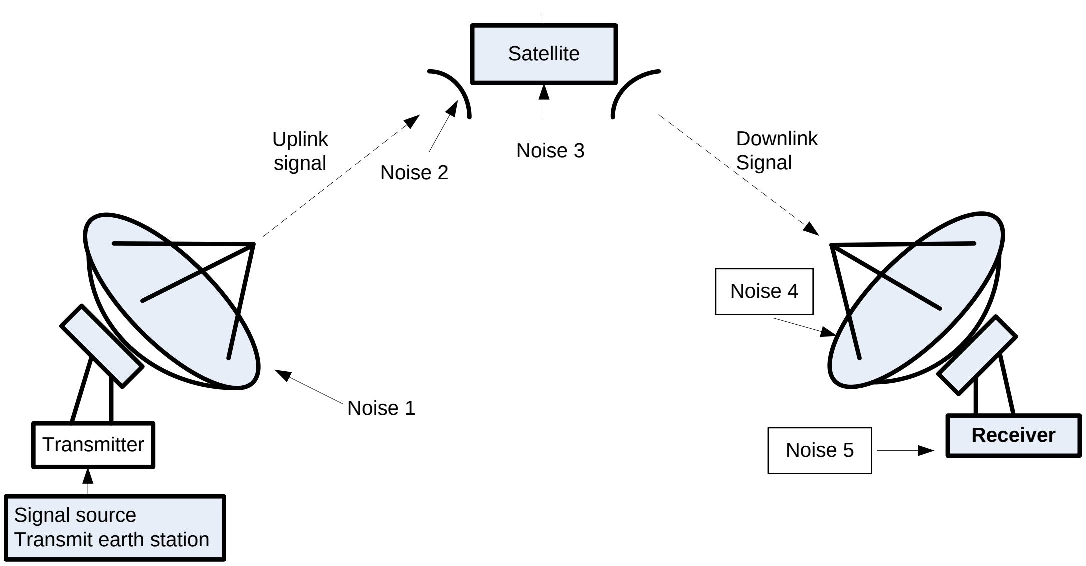


Figure 1.3: Noise distribution in satellite communication system (Adapted from Iida, 2000).

1.3.5 Thermal noise and its effects on the signal

There are several types of noise encountered in electronics, but thermal noise is the most dominant. Thermal noise is considered to be the basic source of noise in RF and microwave components. Thermal noise in electrical circuits manifests in thermal agitation of electrons in resistive circuits components (Basari, 2011:20). Thermal noise of an RF component is seen as the output power of that equipment measured when there is no input signal applied to it. That measured quantity is also known as noise floor. This noise floor represent a danger to the RF equipment as for high power input signals, the equipment will be destroyed and for very low power input signals, the output will be dominated by noise. The noise floor level can be lowered by using cooling elements (Basari, 2011:20-22; Pozar, 2005: 500-493; Scholtz, 2004:36-37).

The receiving side LNA is considered to be the source of thermal noise that can be quantified in the following terms: The root mean square of the voltage generated by thermal source in a resistive circuit is defined in equation (1.1) and the maximum power transferred to the load by the noise source is defined in equation (1.2) (Pozar, 2005)

As it can be seen from equation (1.2), the noise power is directly proportional to the temperature and to the bandwidth. In other words, the smaller the bandwidth, the smaller the noise power. Likewise it is for the temperature. Therefore, the use of cooling devices will decrease the noise power (Pozar, 2005:488) and this corroborates the necessity of a cooling system to keep temperatures within the acceptable temperature limits of operation as to achieve low noise.

At the receiving side, thermal noise consists of noises from different receiver's components namely the antenna, the feed system and the low noise amplifier (LNA) (Iida, 2000:36-37). The total thermal noise is, for the reasons of convenience, expressed in terms of the equivalent input temperature at the receiver's input port. The noise figure is one of the ways to express the temperature in the amplifier.

1.3.6 Noise figure and temperature

The noise figure is an alternative way to characterize noisy microwave or RF component. It gives the measure of the degradation of the signal input to noise ratio at the input and the output of the component. The signal to noise ratio (SNR) is the ratio between the signal power and the noise power. The noise figure remains the same for noiseless component because at the output of the component both the noise and the signal will have been multiplied by the same attenuation or gain. On the contrary, if the microwave amplifier is noisy, the SNR will be reduced at the output, and the noise figure will give the measure of that reduction (Pozar, 2005:493-500).

$$NF = \frac{S_i / N_i}{S_o / N_o} \geq 1 \qquad \text{Equation (1.3)}$$

NF: Noise figure

S_i and N_i: Signal power and noise power at the input port of the component

S_o and N_o: Signal power and noise power at the output port of the component

The noise figure NF can also be expressed in terms of equivalent temperature at the input port of the microwave component:

$$T_i = T_o(NF - 1)(^oK) \qquad \text{Equation (1.4)}$$

T_i is the equivalent input noise temperature

T_o is the physical temperature of circumstances in which the circuit is immersed

The mathematical expression (1.4) shows that the equivalent input temperature directly depends on environmental thermal conditions in which the receiver is located.

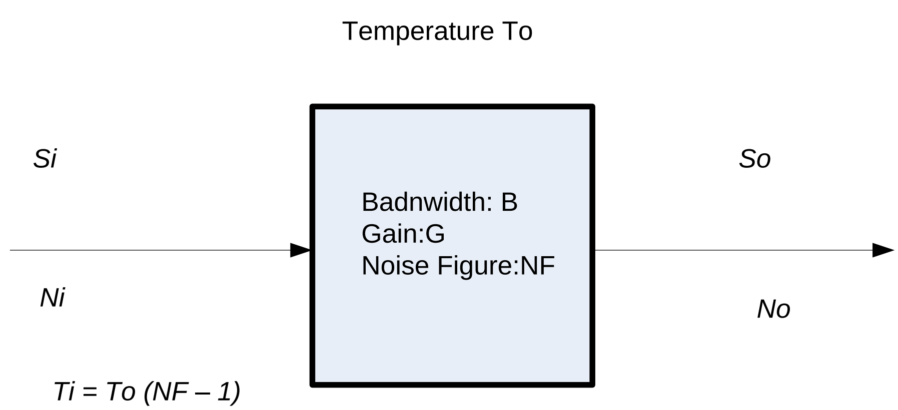


Figure 1.4: Input temperatures as a function of the noise figure (Pozar, 2005).

According to the diagram in Figure 1.4, the noise power is directly proportional to the external thermal conditions expressed as a function of the temperature T_O. This shows once more the importance of having the external environment that is cooler than the RF components environment to allow heat transfer. It is noteworthy to remind that the heat transfer process takes place only in a specific direction - from the hotter environment to the less hot one. In terms of pressure, heat transfer occurs from the higher pressures to the lower pressures. Thus, it is important to keep the external thermal conditions cooler than the internal ones.

1.3.7 The dynamic range of a realistic amplifier

The RF amplifiers are meant to scale the input signal of a factor called gain; and are considered to operate in a linear manner. This implies that the output is in a direct proportion with the input by the factor known as the gain. However, in reality, the amplifiers have limits of operation and cannot amplify any input. The range whereby the amplifier can deliver an output is called the dynamic range. Ideally, the amplifier’s output should be equal to zero when there is no input applied. In practice, this is not the case, because of the noise floor. The noise floor is the output observed when there is no input signal applied to the amplifier, and its source is mainly thermal. The noise floor increases with temperature increase and consequently decreases the dynamic range of the amplifier. As a result, for high signals the amplifier will saturate prematurely and get destroyed in one hand. On the other hand, small input power signals will be dominated by the amplifier noise and will not be detected. For the signal to be detected, it must a little bit above the noise floor (Figure 1.5). The noise floor can be lowered by keeping the LNA in a cold environment.

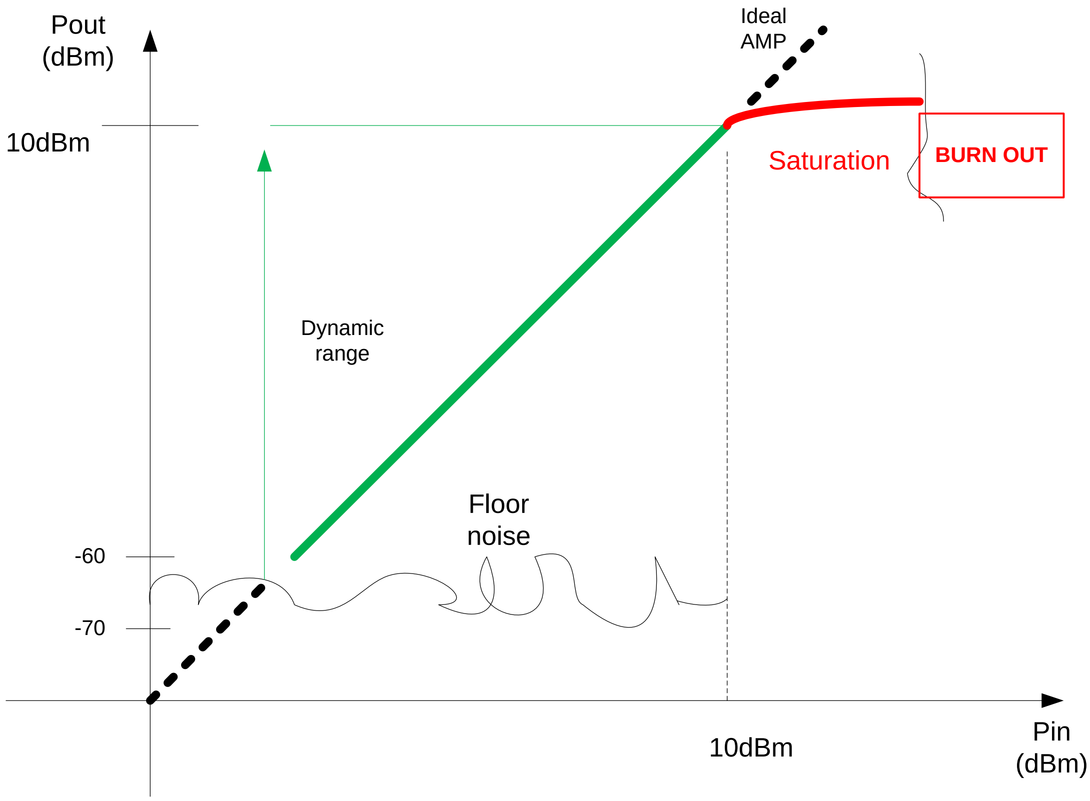


Figure 1.5: The noise floor's effect on the amplifier's life span and performance

(Adapted from Pozar, 2005)

1.4 Research questions

Towards the development of the cooling system for a mobile satellite ground station, a research question can be phrased as follows:

"How cana cooling technology suitable to a mobile ground station be developed? "

From the main research question, sub research questions can be derived taking into account to the welfare of the mission operators that would be onboard of the ground station and to the environment.

"How can a clean, human and environment friendly cooling system for a mobile satellite ground station (MSGS) be developed?"

1.5 About cooling techniques

The cooling techniques that will be looked at in the context of this project comprise the techniques for electronics cooling and the techniques for the MSGS truck cooling.

1.5.1 The cooling of the LNA and of the electronics

RF amplifiers use the same cooling techniques as all the power dissipating electronics. These techniques can be either passive or active (Lasance & Simons, 2005; Trutasanawin & Groll, 2004). But in most cases, the cooling of electronics is limited to passive techniques due to the limited available space on circuit boards and to the power involved in the use of the active cooling techniques.

Regarding the passive cooling techniques, natural heat transfer principles apply via the conduction, convection processes as follows.

- Conduction: It is a heat transfer process that consists of exchanging the heat through the contact of two materials at different thermal conditions. In the case of RF amplifiers and power dissipating equipments, the heat sink is of common use. The heat sink is a passive heat exchanger that cools the device by dissipating the heat in the surrounding air. The heat sink has the property of high thermal conductivity with respect to the device mounted on its surface; the heat does transfer from the latter to heat sink.
- Convection: It is the next step after the conduction. The heat collected by the heat sink is spread in the surrounding environment in order to keep the heat sink colder than the device to be cooled down. The process of convection is achieved by increasing the surface of the heat sinks to the air the use fins or heat spreaders as it is shown on (Figure 1.6).

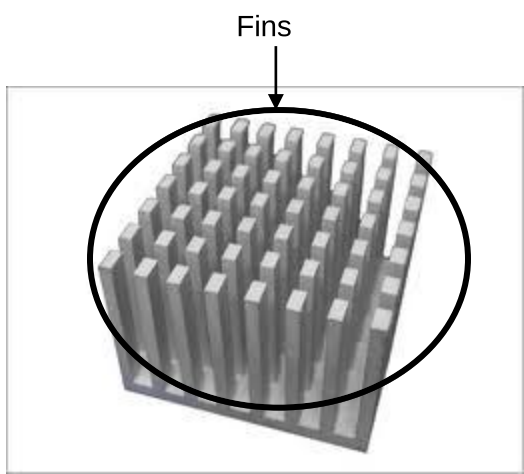


Figure 1.6: Finned heat sink

- Forced air: Forced air technique consists of directing the cooling air through a finned heat sink to speed up the cooling process. This is achieved with the help of cooling fans.

The active cooling of electronic devices, it involves a power source and in many cases a refrigerant fluid. The cooling liquid is pumped through a chill plate thereby cooling the amplifier and other devices in its passage. The cooling exchanger is external to the amplifier. The use of the pump in this cooling technique implies the use of a source of energy to run the pump. The literature conducted so far lead us to the following with regards to electronics cooling.

- The thermosyphon is a cooling technique that uses the water as a refrigerant. It can provide a cooling effect up to a maximum of 80W (Pal *et al*., 2002).
- The loop heat pipe using ammonia/water as cooling fluid can also be used in the electronics cooling with a maximum power of 130W (Maydanik*et al.*, 2005).
- The electrosmotic pumping running on a liquid refrigerant can provide a maximum cooling power of 38W (Jing *et al.*, 2004).
- The impinging jet offers a maximum cooling power of 200W, uses water to cool the electronics (Bintoro*et al*., 2005).
- The thermoelectric microcooler offers a power density of 1000Wcm^{-2} (Fan *et al.*, 2001).
- The vapor compression heat pump can be used to provide a cooling effect of 50W, the isobutene being the refrigerant (Mongia*et al.*, 2006).
- An absorption heat pump can be used in the cooling of electronics whereby it is capable to offer 350W while the water/ lithium bromide is the cooling fluid.

1.5.2 The cooling of the truck

For the cooling of the truck, a preliminary literature on active and passive cooling techniques wasconducted. Geetha and Velraj (2012) gave an overview of passive cooling techniques mostly applied in the domain of construction. Mittal *et al.* (2005), Kim and Ferreira (2008) provided a detailed review on the solar based cooling technologies. The work done by these researchers couldhelp solve thermal problems observed in cooling the SMGS especially looking at the mobile aspect of the truck and at the power supply problems.

1.6 Objective of the project

The objectives of the project are:

i. to design a cooling system suitable to a mobile ground station with regards to thermal noise issues observed at the receive side of a satellite communication
ii. to design a cooling system suitable for the comfort temperatures on board of the truck for the mission operators.

1.7 Research design and research methodology

- To conduct an intensive literature survey on cooling technologies

The literature will be conducted on the cooling technologies in general but will focus on those applicableon mobile structures and do not rely on the national electricity provider for the power source. The literature review will help choose the cooling technology that suits the mobile ground station. The choice of the cooling technology to be used for the mobile ground station will depend on a couple of factors such as the efficiency, the cost and the size.

- The development of the cooling system

The developments of the cooling system willfirst have to quantify the effect of temperature on the signal and the amplifier. The effect of the temperature will be quantified based on the specifications of the FSATI's LNA, the MSP432-VDG-160, located at the ground station. In this context, a mathematical model of the thermal noise, the bandwidth of the LNA and the operating temperatures will help simulate the effects of thermal noise on the signal quality and on the LNA lifespan. Towards the system development, the cooling systems parameters will be required. These parameters will be obtained from the critical values as they will be observed from the effects of the temperature on the signal and the amplifier. Regarding the cooling of the truck, the cooling system will be designed as to meet the comfortable temperatures for the mission operators.

- To simulate and design the cooling system

Prior to implementing the design, simulations will have to take place to predict what is to be expected from the actual cooling system. The simulation of cooling systems are known to be performed on TRNSYS platforms (Albers *et al*, 2008; Petrenko&Shestopalov, 2011; Eicker&Petruschka, 2009); Matlab and PSIM will be used in simulating the power part of the project.

1.8 Delineation of the project

The project will limit itself on the cubeSat mobile station of the same capacity as the FSATI's fixed ground station and focus will be on the receiving end. Figure 1.7 shows the boundaries of the project's focus. With regards to the system development, efforts shall be put in the part concerned with the power supply to the cooling system since cooling units of various types and sizes are available in the market.

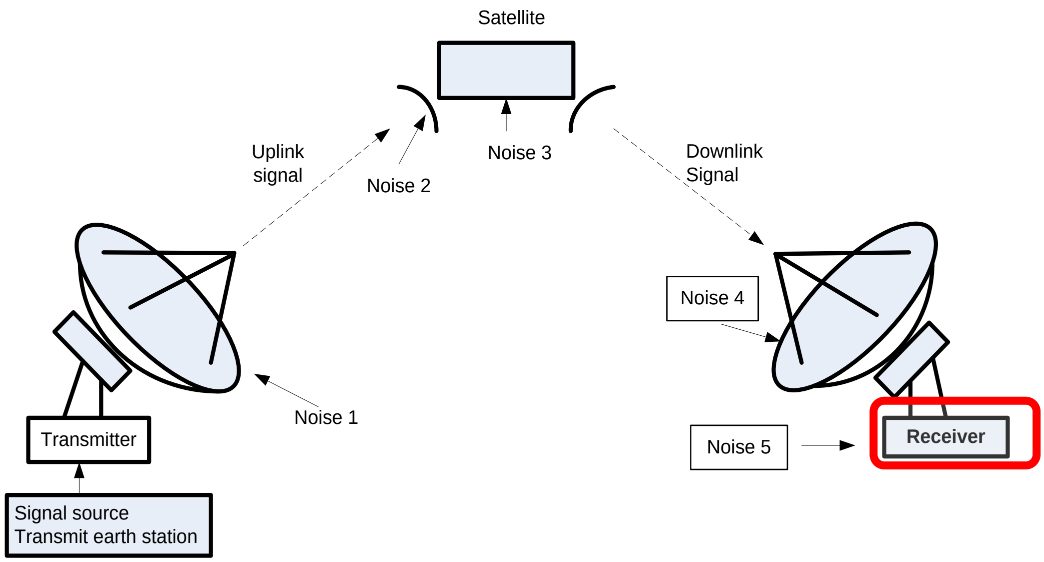


Figure 1.7: Delineation of the project.

1.9 Significance of the research

The research will benefit the CPUT-FSATI's satellite system with regards to the quality of the signal received. The introduction of a cooled mobile station will enhancethe flexibility of operation, broad coverage for the satellite network with a higher sensitivity receiver. Nationwide, South African National Space Agency (SANSA) may make use of the technology to improve satellite communication systems.

1.10 Expected outcome

The outcome of the project is the design of the cooling system that will be referred to when the project of mobile satellite ground station will be developed. This design will be accompanied by a well-tailored thesis and a journal submission to accredited department of Higher education and training (DHET). The work will add more literature with regards to the cooling technologies especially of mobile structures. So far, a conference paper of the same title as the thesis has been accepted and presented in the 10th Industrial andCommercial Use of Energy (ICUE) conferenceheld from the 19 to 21st August 2013 at Newlands in Cape Town (Kamanzi and Kahn, 2013).

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

The chapter two of this thesis introduces the concept of cooling technology and discusses the low energy cooling technologies and renewable energy related air conditioning and refrigeration as applied in the field of construction. The part of the conventional cooling techniques in the global energy crisis and in the global warming has been pointed out. The necessity of using passive techniques for air-conditioning purposes has been raised to circumvent the global energy crisis. Active cooling techniques were overviewed as well. Though all these techniques are a peculiarity to the building air conditioning, they can be applied in the cooling of a mobile satellite ground station based on the structural point of view. Thus, the techniques applied in the domain of constructions can be implemented to some extent in the process of cooling a mobile ground station during hot seasons. The cooling methods of the electronic devices have been overviewed as well since for the sake of the LNA of which the performance and the lifespan are affected by thermal increase generated within the same components.

2.1.1 Cooling concept and effects of conventional cooling

Cooling can be defined as a process of transferring the heat energy from the air to the desired space or vice versa, in order to bring a desired space to a thermal comfort (Geetha&Velraj, 2012). In the building sector, cooling techniques are also known as air conditioning (AC). The AC system's purpose is to bring thermal comfort and acceptable indoor air quality into buildings for the sake of the occupants (Yu *et al.,* 2009).The cooling techniques find applications also in industries whereby some processes occur at very high temperatures, while the ambient temperature must be kept at low temperatures. In this same application, processes may need to be brought from high temperatures to low temperatures by means of a cooling cycle. Likewise, in the framework of this project, the container of the ground station equipments must be kept at allowable temperatures for the sake of the components borne in the truck hosting the mobile ground station.

Cooling processes can take place naturally or have to resort to another source of energy to be able to transfer heat from one medium to another. The natural cooling techniques fall in the category of passive cooling, for no other input energy than the natural renewable energy source is involved in the heat transfer process. Sometimes, in order to enhance the efficiency of passive cooling techniques, low energy mechanical source get involved to remarkably increase the effectiveness of the system. In this case, the process becomes hybrid.

Besides passive techniques, there are active cooling techniques as well. Active cooling systems are those involving external source of energy in order to achieve heat transfer. The active cooling in buildings has been singled out as one of the most power consuming sectors alongside the lighting and the heating. This comes mainly as a result of the rapid economic growth worldwide. The contribution of buildings' power consumption has been approximated to 40% of the total global energy per year(Kamal, 2012) of which 10% is the part of the cooling and AC systems in offices and commercial buildings (Lain &Hensen, 2006; Geetha&Velraj, 2011). The power consumption by these systems reaches their peak values during hot seasons due to the high temperature gradients. The high demands in terms of energy have led to the use of fossil fuels which consequently are responsible for the environmental problems the globe is currently experiencing (Brita in Pubs, 2007). The world has faced the climate changes, the global warming, and environmental degradation due to the intensive use of fuel cells.

Apart from the energy consumption issues, traditional cooling technologies are directly involved in the global warming and climate changes via the refrigerants used in the cooling process. The classical refrigerants used in the conventional cooling technologies have either ozone-depletion potential (ODP) or global warming potential (GWP) (Brita in Pubs, 2007; Mugnier&Jakob, 2012).

Furthermore, studies have shown that AC systems in buildings are at the origin of indoor diseases (Sappanen& Fisk, 2002). According to the authors, there was more prevalence of sick building syndrome (SBS) in the air-conditioned buildings than in the ventilated ones. The SBS can be defined as a combination of ailments linked to the place of work or residence; and it is mainly due to the poor indoor air quality. The authors have estimated the prevalence of that disease between 30% and 200%. They also stipulated that death caused by the legionnaire disease, a fatal respiratory disease, is mostly found in buildings comforted with AC systems (Yu *et al.*, 2008).

2.2 Passive cooling techniques

Passive cooling techniques are those which do not require an external power source to provide the cooling effect and offer some advantages over the active techniques. The concerns observed in the utilization of active cooling and air conditioning systems lead to adopting natural techniques and other techniques that are unharmful to both the human livings and the environment. In this framework, Geetha and Velraj (2012) have conducted a study on how to achieve the cooling of buildings with the help of passive techniques and processes. According to the authors, the cooling can be achieved in three different ways: reducing the heat gains, thermal moderation and removing the heat within the buildings.

2.2.1 Reduction of heat gains

The reduction of heat gains consists mainly of limiting thermal solar irradiation entering a building. The solar energy intakes into the building will depend upon the climate or the microclimate of the region. The climate can be defined as the average atmospheric conditions over an extended time over a large region whereas the microclimate represents the small scale pattern of the climate. The microclimate can be influenced by some factors such as the topography, the soil structure, the ground or the urban forms. The microclimates of the cities are different to those of surrounding rural areas. Urban areas climates are characterized by ambient temperatures, reduced humidity, reduced wind speed and reduced direct solar radiation. This is due to the presence of highly dense tall buildings at a high density and to the quasi absence of green space and water surfaces. Blue and green surfaces can then be involved in the solution of limiting the heat gains in urban areas. Therefore, the techniques put in place will be in the forms of landscaping, vegetation and water surfaces. This can be implemented on public places, parks and play grounds. Parks, green and blue spaces can hugely contribute to the cooling during the summer through shading, wind driven ventilation (Liu &Baskaran, 2003; Yu &Hien, 2006; Shashua*et al.*, 2004). The green areas are being used on rooftops and wallsofbuildings(Givoni, 1991).

2.2.2 Solar radiation control

One of the best way of bringing comfort to the building is to control the amount of solar radiation reaching the inside the building. Solar control should ensure that the amount of solar radiation is minimum during cold seasons and maximum during hot seasons. Solar radiation comes to the external surfaces of the building in various forms: direct, diffuse and reflected. Some solar control techniques have been adopted in the following aspects: apertures, glazing, insulation and shading.

The apertures form the group of all the openings on the building's external envelope. The size and tilt of the apertures command the incoming radiation. In one hand, the design of a building should be such that the apertures would allow the minimum solar radiation in summer and the maximum amount in winter (Mazria, 1979). To achieve this, buildings must have their windows facing the south in the northern hemisphere; and their windows facing the north in the southern hemisphere. In fact, this recommended orientation allows to the sun pass in front of the building, façade containing windows and main apertures. During the winter, the incident solar radiation reaches the windows from the front at small angles and most of it passes trough. During the summer, the sun is high and the solar radiation reaches the apertures at large angles and passes almost parallel to the apertures or simply at the back of the building (Passive Solar Design Primer, 1998).This design can reduce heating and cooling costs up to 85% (Green Passive Solar) (Figure 2.1).Still, regarding thermal control, the design of the building is governed by the index called the aspect ratio (Demirbilek et *al.*, 1994). The aspect ratio is an index that relates the building's parameters namely the floor area and the height with regards to the allowable amount of solar radiation.

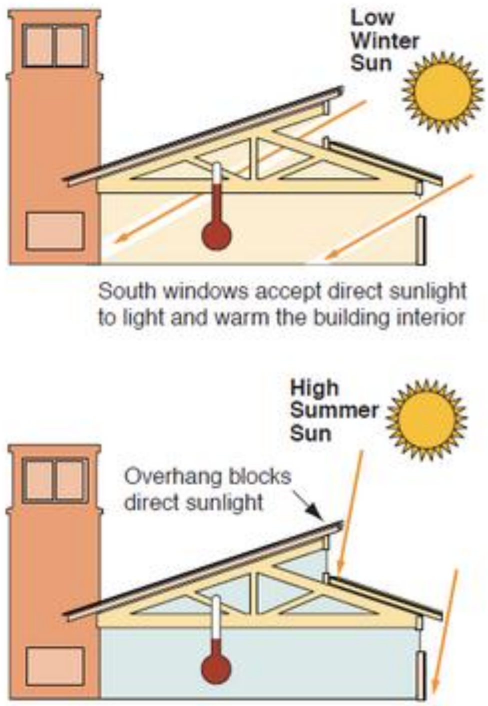


Figure 2.1: Solar radiation enters the building during winter and does not during summer.

The glazing is another way of controlling the sun radiation by exploiting thermal properties of windows and all the transparent sides of the building. The heating performance through glazing is a function of the size of all openings (inlets and outlets) and of the channel width of the glazing. The channel width determines the amount of solar radiation that can pass through the glazing per unit of area. The increase in the glazing governs the increase in the flow rate of solar radiation and is profitable for heating the buildings in winter time. For summer time, insulation of interior surfaces contributes in the fighting against the overheating effect.

However, the overall performance is linked to the properties of the material constituent of the glazing. These properties govern theselection ofthe amount and the type of solar radiation passing through the glazing; and most of the thermal heat is conveyed through Infra Red radiation. Successful researches regarding solar radiation control have been conducted and their output is ready for use already. According to Hutchins (2003), thin films optically selective surfaces have been promoted for efficient conversion and control of visible, solar and thermal radiation. Solar control coatings selectively transmit the incident visible light and reflect the near Infra Red solar radiation Dynamic transmittance apertures hugely contribute in preventing the overheating inside the buildings and in reducing glare problems during the peak periods of heat sun. In fact, the glazing material must be able to allow the visible daylight through and to let in the building the necessary thermal radiance for comfort purposes. In this context, the following technologies and materials have been resorted to: Low emittence window systems, low thermal transmittance, vacuum glazing, electrochromic windows, thermotropic material, silica aerogels and transparent insulation materials (Lampert&Granqvist, 1990; Georg *et al.*, 1998). Angular selective glazings hugely participate in attenuating the intensity of the direct solar radiation; the latter being known to be the main source of the glaring (Smith *etal.*, 1998).

2.2.3 Insulation

In the cooling of buildings, insulation is a process of increasing the thermal resistance of the external envelope. This process is commonly implemented on roofs. Investigations have been conducted regarding the insulation techniques and some results have been recorded. Belusko*et al.* (2011) have studied the insulation made on the basis of a timber framed pitched roof. They have reached to the conclusion that this technique has results twice better than those of the two dimensional bridging. Ong (2011) has studied the use of solar collectors in the attic under the roof to provide both efficient ventilation and cooling.

2.2.4 Shading

Shading consists of the obstruction – total or partial of the sunbeam directed to a building's surface in order to reduce the amount of solar radiation on that surface by using a surface object. Then, the resulting shadow will have a variable position and size depending upon the geometric relationship between the sun and the surface under study. Studies in this regards have been carried out and satisfactory results have been achieved (Clarke, 2001; Li *et al.*, 2004; Ho *etal.*, 2008). Material properties such as thermal emittence and thermal transmittance play an important role in the solar heat control.

Thermal emittance: In buildings, some parts such as apertures and roofing are dedicated to handle the incoming solar radiation. They are made of the material that absorbs the solar radiation, let pass a part of it and reflect back another part. Thermal emittance can be defined as the power [Watt] released by a material per unit of surface area [m^2]. Thermal emittance plays an important role in the heating and cooling of buildings. For instance, roofing surfaces with high emittance will absorb the solar radiation and reflect it back almost entirely. In winter, with the sun more exposed to the windows, the latter should have a low thermal emittance and then let most of the solar radiation in the building.

Thermal transmittance is the rate of heat transfer [Watt] through one square m of a structure per temperature difference between the environmental temperatures on each side of the structure in the absence of the solar radiation. Also known as U-factor, it is expressed in [$Watt.m^{-2}.K^{-1}$]. In buildings, well insulated parts are meant to have a low thermal transmittance whereas poorly insulated parts are known for high thermal transmittance.

2.3 Heat modulation or amortization technique

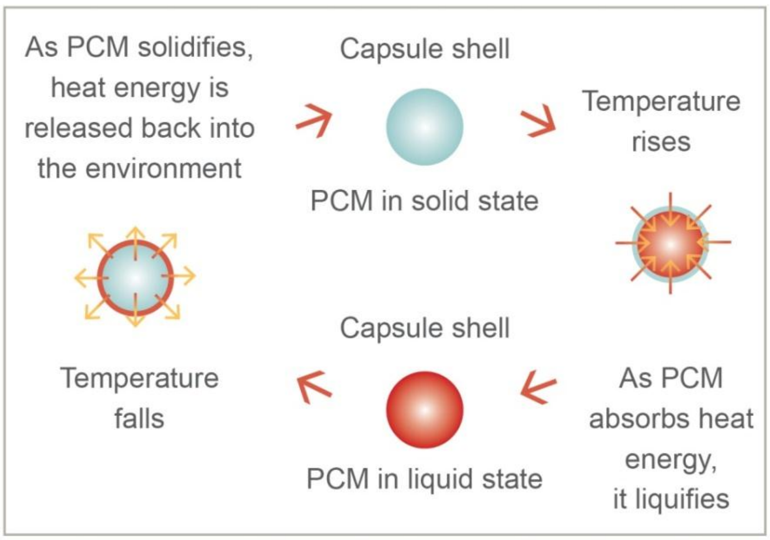
Heat modulation is a technique that operates by modifying the solar heat gains in the buildings. Solar heat gain simply refers to the increase of temperature that a space or an object experiences from the solar radiation. The solar heat gain can be modified by using two main techniques.

2.3.1 Shifting the day heat to night for removal

The heat inside the building acquired during the daycanbe removed in two ways. The first way consists of using the mass of the building to amortize the heat. The walls, the floors and the other parts of the envelope are made of materials with high heat capacity in order to absorb the heat from the day solar radiation, store it and release it during the night to bring comfort to the buildings. The night ventilation is a techniqueof cooling an unoccupied building during the night via the night ventilation process; the resulting cooling energy is stored and released by the early hours of the following day. This cooling technique suits the best to business and administration buildings or bureaus. Night ventilation process occurs during the night whereby the indoors high temperatures are lowered by outdoors low temperatures (IEA, 1995). Night ventilation improves the comfort of the building during the night whilst decreasing peak loads the following day. Again, the structural mass plays a significant role in the cooling of HVAC fitted buildings. In fact, the bigger the cooled mass, the higher the cooling zone peak - temperature set points, the lower the peak load demands. The cooling set point is referred to as a desired value in a closed loop feedback system in the process of temperature regulation. Past this point, the active cooling system starts off.

2.3.1.1 Phase change materials

Phase Change Materials (PCMs) are materials made of substance with high heat of fusion, melting or solidifying at a certain temperature. With this property, they can store large amounts of heat energy and release it during the times of temperature swings. Temperature swings refer to the variation in temperatures due to the heat of the day and the cold of the night. The PCMs change from solid to liquid during the absorption of the heat and undergo a reverse process when they are releasing the heat. Thus, they are called latent heat storage units.PCMs are also considered to provide the free cooling whereby no electrical power is involved in the cooling process. PCMs can be integrated in wallboards, roof (and ceiling) and windows strategic points to achieve the heat exchange for cooling of building (Pasupathy*etal.*, 2008).



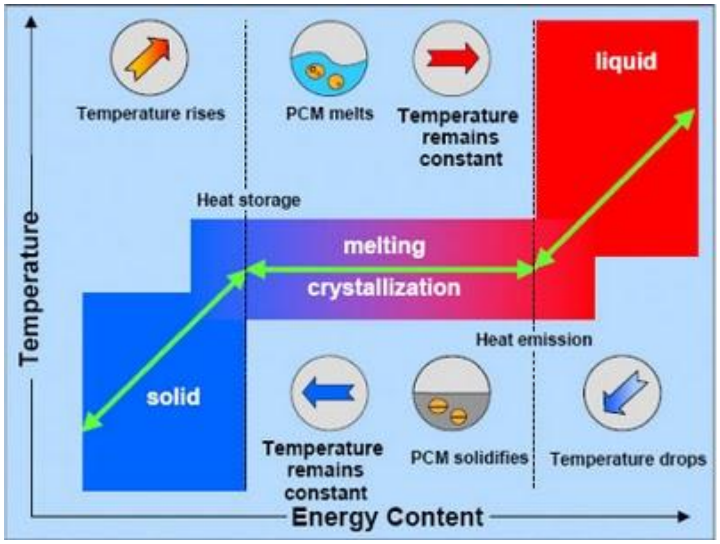


Figure 2.2: Illustration of the heat exchange in the phase change material

2.3.1.2 PCMs in wallboards

The walls constitute the major part of the masse of the house and are convenient to use regarding the integration of PCMtechnologies. PCMs can either be applied to the wall boards in forms of layers, process is known as "attachment" or mixed with the material constituent of the concrete, process known as "immersion" (Ghetta&Velraj, 2012).

The attachment technique is achieved by applying layers of PCM integrated wallboards onto the walls. These wallboards are applied indoors after the construction of the building's envelope and can be designed in the sort of decoration for the sake of the indoors' look. Various researches have proved that the PCMs integrated walls are much better than the walls constructed basing on the conventional masonry (Bernard *et al*., 1985; Khalifa*et al.,* 2009; Ghoneim*et al.*, 1991)

The immersion technique is based on a threefold concept: The direct immersion, the macroencapsulationand the microencapsulation. However, the immersion with the microencapsulated PCM is the most common because of the advantages it offers as compared to the two other techniques (Sharma*et al.*, 2009). The direct immersion of the PCM in the envelope has the inconveniences such as leakages and the envelope shape distortions along with handling and maintenance problems. The macroencapsulation immersion, due to the relative capsule size, is difficult to achieve the optimum thermal inertia with. According to the same author, the experience has proved that no success has been recorded with these two methods so far. The microencapsulation immersion is implemented with the encapsulation of micro – sized polymer and membrane where it allows achieving high thermal inertia when compared the other methods.

2.3.1.3 PCM in roof and ceiling

In the roof and ceiling on the base of the PCM can help achieve thermal storage capacity matching the heat gains observed during the day time inside a building. In fact, during the daytime, the ceiling is exposed to all indoors' sources and acts as a sink whereas it acts as a heat source during the night. The development of lightweight PCM ceiling panels has been achieved with the help of a microencapsulated PCM and gypsum along with capillary tubes and aluminum for a better heat transfer performance (Koschenz& Lehmann, 2004). The heat energy absorbed by the PCM during the daytime can be released either through the natural night ventilation or chilled water circulating in the capillary tubes. Several researches have proved that PCM ceiling assisted with chilled water offer better performances than the cooling systems operating on the basis of the traditional system of chilled water only (Griffiths & Eames, 2007; Wang &Niu, 2009). However, Pasupathy and Velraj (2008) advise the use of a PCM double layer in the roof in order to achieve the passive cooling throughout the whole year.

2.3.1.4 PCM in the windows

On the envelope of a building, the windows constitute the part with less thermal resistance. Thermal resistance is the ability of absorbing heat energy and releasing it in the process of temperature swings. Due to the difficulties observed in integrating the PCM in the glazing, only few studies were carried out in this regard. Ismail *et al.* (2008), one of the researchers has proved the possibility of integrating the PCM in a widow within a double layer glass. Conclusions are such that the phase shift material must be squeezed between two layers of glazing and be kept at the solid state during winter time; change their solid state to a liquid state as the exterior temperature increases – during summer time.

2.3.2 Natural cooling

The natural cooling is a cooling technique that consists of dissipating the heat through natural processes. The heat dissipation technique refers to the heat rejection to the heat sinks by the means of the natural processes of heat transfer. The excessive heat inside the building is rejected via the natural cooling techniques of which the performance depends upon the building's design. The natural ventilation is one of the most used for the passive cooling technique. It works by the infiltration of outdoors air into the building's space to be cooled. However, the natural ventilation technique does not find use in modern buildings whereby the outside environment is tightly isolated from the inside. This is done in order to avoid the influence of the outdoors environment to the interior of the buildings. In old aged buildings, the natural ventilation was enhanced by the open windows (Ghetta&Velraj, 2012). In the context of this project, the natural ventilation cannot help since the container of the mobile ground station must be kept tightly sealed for the safety of the RF equipments and other electronics contained within the truck.

2.3.2.1 Night ventilation techniques

Night ventilation technique consists of the heat exchange between two media having different temperatures. During the night, the ambient temperatures are low as compared to indoors and the building's structure temperatures. Thermal exchange takes place between the cold outdoors and the hot indoors via the building's envelope. The success of the night ventilation processes depends on two main factors: the flow of the cold air and the thermal mass of the building. The two factors must have a certain balance in order to avoid colder nights and hotter days. So far, successful studies have been recorded regarding the use of night ventilation in building cooled passively even in European countries where winters are terribly cold (Santamouris *et al.*, 1996; Blondeau *et al.*, 1997; Kolokotroni *et al.*, 1999). However, various ideas from researchers are somewhat showing the inefficiency of the night ventilation regarding the cooling of the buildings whilst agreeing on the importance of the thermal mass in the process. Studies suggest that the night ventilation must be supported with exhaust fans to be effective and that the technique can perform better in buildings with high mass than lightweight buildings and the daily air temperature range should be around 8^{0}C and the night temperatures should not be too low (Blondeau*et al*., 1997; Carrilho da Graca*et al*., 2002; Santamouris&Wouters,2006).

2.3.2.2 Evaporative cooling

The evaporative cooling can be defined as a passive cooling technique that uses the evaporation as a heat sink. Two agents are involved in the process: The hot air and the liquid that will undergo the evaporation. In many cases, water is used. During the process of evaporative cooling, the principle of heat transfers applies. Hotter air moves in the direction of cold air whereby a liquid undergoes evaporation. During the transition of water to water vapors, the temperature of dry air drops considerably, then contributing to the cooling of the desired space. This process can be achieved by disposing water in the hood of the building in the form of ponds, fountains, pools or spray (Ghetta & Velraj, 2012). The same authors suggest the use of a porous material saturated with water or another process called evapotranspiration. The evapotranspiration is the process that involves vegetation. The evapotranspiration is a process whereby a plant transpires as to reject heat and thus providing a cooling effect. Several hundreds of kWh per year spent on AC systems can be saved by one tree (Orosa&Oliveria, 2012). Unlike the conventional AC systems working on basis of the closed loop cycle, the natural evaporative cooling works in an open loop. In other words, the evaporation process is not reversible and the continuous water supply should be guaranteed.

2.3.2.3 Ground cooling

The ground cooling technique relies on the fact that the ground temperatures are lower than the outdoors environment during the sunny times. The cooling process is achieved by virtue of the heat transfer principle. The heat energy can be dissipated to the ground by the direct contact between the building's envelopes or by admitting into the building the air coming from the ground. The air is circulated to the ground prior to getting into the building by means of earth-to-air heat exchangers. The heat exchanges between the envelope and the ground is done by conduction; and its effect in terms of cooling is small as compared to the effect observed from the convection and radiation respectively.

2.3.2.4 Radiative cooling

Radiative cooling is the technique that consists of the heat loss by long wave radiation from one body to another of lower temperature. This technique is the direct application of the heat transfer from source to sink. Radiative cooling that can be either implemented by using a direct or a passive method whereby the external envelope of the structure will be used to radiate the heat to the sky therefore creating heat loss in the building or structure. Radiative cooling can also be achieved by using a hybrid method where an intermediate flat metal is used to radiate the heat from a structure (Raj &Velraj, 2010). According to these same authors passive radiating cooling is basically achieved by using a white paint on the roof and possibly on the overall external envelope. White paint has an emissivity on long range waves so as to absorb less solar radiation during the day time. As for the radiative hybrid cooling, the authors suggest the movable insulation system and the flat plate air cooler. The movable insulation system has two variants: The first variant consists of an insulating material that is fitted to the roof of the structure so as to cover the roof during the day time whilst absorbing solar radiation and therefore preventing heat gains inside the structure. The second variant of movable insulation is the movable thermal mass that requires the construction of a thermally insulated pond on the roof of a structure. The pond, a bit separated from the roof, is covered by a movable insulation device so that water can flow to the roof via canalizations from the pond to the roof. The flat plate air cooler works in asimilar way to a solar collector cooler linked to a storage tank. The device isa rectangular duct of which the top is made of radiative material with high remission index in the long wave range of the electromagnetic spectrum (Musseli, 2010).

2.4 Active air conditioning and refrigeration technologies

This section discusses in detail the active cooling technology. Conventional refrigeration and air conditioning systems have been overviewed. The classical vapor compression refrigeration system together with all the cooling systems running on electric power have been named along with their working principles and applications. Focus has been put on electric powered refrigeration cycles. In the same way, solar thermal driven cooling technologies were spoken about. Their efficiency commonly known as the coefficient of performance has was pointed out in each case.

2.4.1 Cooling technologies

In cooling systems, the cooling effect is provided by the chillers. Chilled water is distributed to heat exchanger, coils, air handling unit or other terminal devices that cool the air in their respective space and then the water returns to the chiller. The coils or terminal devices transfer sensible from the space to be cooled to the chilled water therefore cooling the air. There are two main types of chillers namely the vapor compression chillers and the sorption chillers.

2.4.2 Vapor compression cooling systems

Vapor compression cooling systems are composed of three main components namely the compressor, the condenser, the evaporator (Figure 2.1) and the expansion device. In addition to these components, there are accessories such as the controls, filters, the driers and the oil separators just to name the essentials (Nawaz*et al.*, 2012). The compressor is the component that must provide the work to run the cooling system. The condenser and the evaporator play the role of heat exchanger whereby a refrigerant undergoes the change of phase.

2.4.2.1 The cooling effect

The cooling effect takes place in the evaporator where the refrigerant is evaporated at low pressure and low temperature by the heat of the space to be cooled. The vapors of the refrigerant are released by an expansion device therefore providing the cold effect. The refrigerant's vapors pass through the compressor whereby they get under high pressure. From the compressor, the vapors go to the condenser where the heat acquired from the environment to be cooled is removed from the refrigerant gas so as to recover a liquid refrigerant. The heat migrates from the refrigerant gas to the air or water.

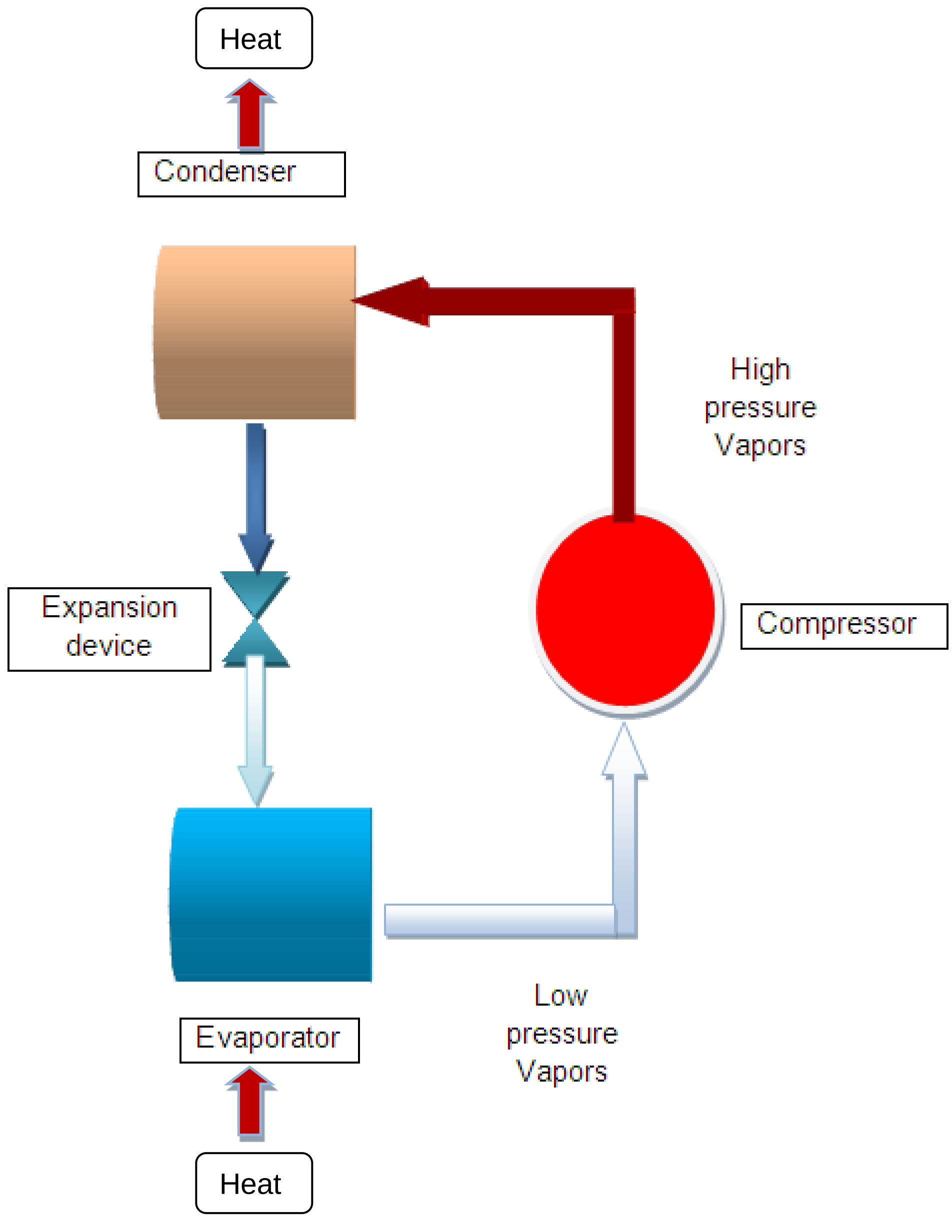


Figure 2.3: Compressor cooling (Adapted from Lim *et al.,* 2009).

The refrigerant passes through the expansion device where they undergo a pressure drop and once again cool the hot environment. Then, the cycle restarts. In this cycle, the evaporator and the condenser are called heat exchanger because they respectively drive away heat from the refrigerant and they absorb heat into the refrigerant's vapors.

The expansion device, also called the refrigerant metering device (RMD), restricts the flow of the refrigerant from the compressor whereby the resulting pressure drop causes the vaporization of some of the refrigerant. This vaporization takes place along with the absorption of the heat from the nearby fluid. The amount of the heat absorbed in the process of refrigerant vaporization is determined by the amount of the refrigerant allowed through the expansion device.

2.4.2.2 The cooling system efficiency

The efficiency of the cooling system is measured in terms of the heat exchangers' performance. The performance of the condenser is its ability of rejecting heat from the refrigerant whilst the performance of the evaporator is its ability to absorb the heat from the nearby environment. This rate of heat rejection or heat absorption is known as the coefficient of performance (COP). The coefficient of performance is the ratio of the cooling power over the input power.

$$COP = \frac{\text{Cooling(Heating) Power}}{\text{Input Power}} \qquad \text{Equation (2.1)}$$

The input power to the compressor is required for the compressor to provide the work under the electrical form to drive a cooling cycle. The limitations in the use of conventional power in the case of a satellite mobile ground station are obvious. Also, in the case of a satellite mobile ground station, the only source of electrical power reliable is the solar energy. Also a variety of other solar based cooling systems that are not electricity reliant are discussed in order to explore which technology suits the best to the satellite mobile ground station applications

2.4.2.3 Sorption based cooling technology

Sorption can be defined as a physical and chemical process by which one substance becomes attached into or onto another. The sorption can take place in two ways: The first way is the absorption which is the incorporation of a substance in one state into another of a different state. In the absorption, a liquid can be absorbed by a solid or a gas can be absorbed by a liquid. The second way is the adsorption, a phenomenon which consists of the physical adherence or binding of ions and molecules onto the surface of another phase. Reagents get adsorbed to a solid catalyst surface.

The sorption based cooling concept exists since ages. It was discovered by Faraday (1823) when he was conducting a study on the ammonia a gas compound. In his study, he wanted to get the liquid ammonia and study it through the solid sorption process. He used the adsorption of a large amount of ammonia on the silver chloride deposited at the basis of the thermal compressor. The experiment conducted in a two leg bent glass with one leg containing the ammoniated solution on the thermal compressor and the second leg where Faraday could collect the condensed pure liquid ammonia. During his experiment, he also noted that: "*When the chloride silver is allowed to cool, the ammonia returns to it, combining with it, and combining* *the original compound. During this action, a curious combination of effects takes place: As the chloride absorbs the ammonia, heat is produced, the temperature rising up to 100ºC whilst few inch off, at the opposite of the tube, considerable cold is produced by the evaporation of the fluid*" (Critoph, 2012).

Sorption cooling systems can be classified according to the type of cycle into two main categories:

i) Open loop systems and
ii) Closed loop systems.

In an open loop system, the evaporated desiccant is released to the surrounding environment. In an open loop system the evaporated water is re-condensed within the chilling machine. The commonly known closed systems are the absorption and adsorption whilst the desiccant cooling is the most known open system. In terms of driving energy, sorption systems run on heat energy. This heat energy used to create high temperatures and pressures in the generator and thus, help the sorption system fulfill the same work as the compressor. The heat can be obtained from diverse sources such as the heat waste, solar heat, fuel based heat or heat cogenerated from more than one source. The heat must be stored in a storage tank in the form of hot water of which the temperature is higher than 70ºC (Ahmed, 2011).

2.4.3 Solar based cooling technologies

Solar energy is known to be the form of energy that is available at no cost and is inexhaustible. On daily basis, the earth receives 10^8kWh. In terms of oil, this amount of solar energy is estimated to an equivalent 500 000 billions oil barrels, an oil reserve unknown in the history of the earth so far (Mittal*et al*., 2005). In the field of cooling technologies, solar energy can be utilized in twowaysnamelythe solar thermal cooling and the solar electrical cooling. The amount of solar energy received is a function of some factors such as the solar collectors, the altitude and the sky status. It is available only during the day time. Solar energy offers some advantages regarding the maintenance and operation costs. Moreover, it represents no harm to the environment unlike fossil fuels. So far, solar energy has been invested in heating water for residences and in the electrical power generation. For water heating, the solar radiation is harvested by solar collectors and converted into thermal energy useful for heating water. As regards the electrical power generation, solar radiation is received by photovoltaic cells that in turn convert the solar radiation into electrical power. In 1986, a solar pilot power plant got built in USA (Friefeld & Colemann, 1986). In Japan, 1 MW output experimental power plants were built (Tsanaka, 1989). Besides the two mentioned applications, solar energy has been in invested in the cooling of buildings. Studies have shown the possibility of using solar energy in the cooling of buildings especially during the hot summer season and in countries with high solar radiation intensity.

2.4.4 Solar electric cooling

Cooling technologies are classified into two main groups namely: electrically powered cooling systems and thermally driven cooling systems (Mittal *et al.*, 2005). As both technologies can be achieved by using solar energy, it is a great opportunity to exploit the same solar energy, which is the research problem of this project, to solve the same problem. Electrically powered cooling systems can be supplied in power thanks to the photovoltaic cells to drive a vapor compression refrigeration cycle, a thermo electric refrigeration cycle or a Stirling refrigeration cycle. With electrically powered cooling systems down to freezing temperatures can be achieved.

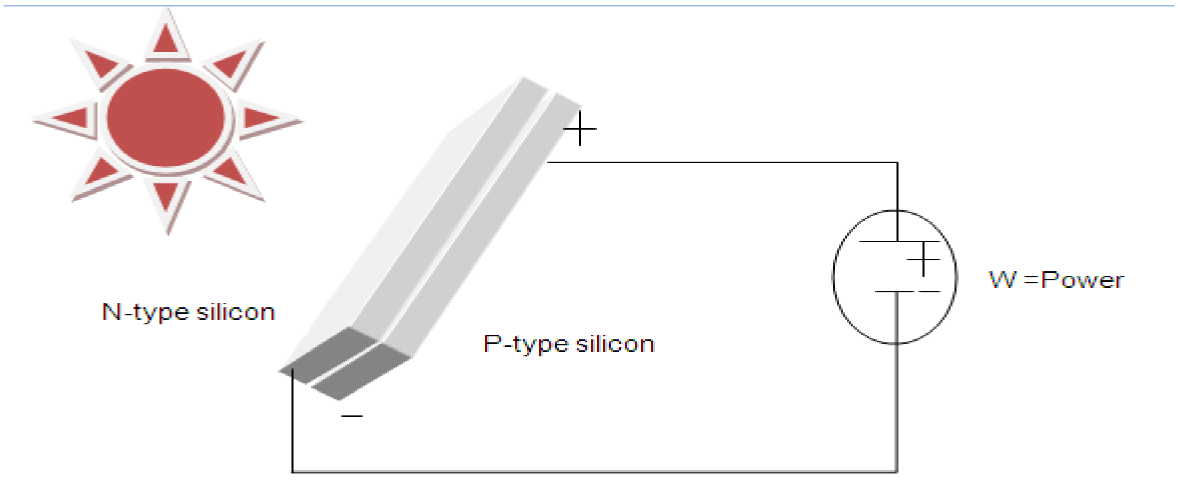


Figure 2.4: Theprinciple of the conversion of solar radiation into the electrical energy

The performance of a solar electric system relies on the material and the manufacturing methods of the photovoltaic cells regardless of the weather conditions. Silicon has been the common material from which the commercial PV cells have been manufactured (Kim &Infante, 2008). The amount of electrical power (W_E)expectedfrom a PV system is determined by the product of the two parameters: the area of the PV cell (A) in $m^2$and the direct irradiation of the solar beam (I_P) in kW/m ^{2} (Equation 2.2)

$$W_E = AxI_P \qquad \text{Equation (2.2)}$$

Also, the performance of a solar electric refrigeration system is determined based on its efficiency. The efficiency of a solar electrical system is defined as the ratio of the measured power over the solar power(Equation 2.3).The highest efficiency observed in PV cells on the market is 15% (Kim &Infante, 2008). When the PV system is integrated in a building, the efficiency of a PV cell becomes about 10% under the direct sun radiation at mid-day (Fanney*et al.,* 2003).

$$\eta_{solar\text{-}power} = \frac{W}{Q_{solar}} \qquad \text{Equation (2.3)}$$

2.4.4.1 Solar electric vapour compression

The solar electric system in the Figure 2.5 can be connected to a DC motor and drive a compressor. The efficiency of the cooling system with respect to the work done by the compressor is given by the equation2.4.

$$\eta_{cooling\text{-}power} = \frac{Q_e}{W} \qquad \text{Equation (2.4)}$$

The system's overall efficiency will be depending upon the efficiency of PV cell and that of the compressor. The compressor's efficiency is defined as the ratio of the cooling poweroverthe input electrical power. The cooling system's efficiency (ŋ) will be the cooling power to the PV power as shown in the equation (2.5).The cooling power is determined by the performance of the evaporator (Q_e). This efficiency is also known as the cooling-to-solar efficiency. In thermodynamics, this efficiency is called thecoefficientof performance (COP).

$$\eta_{solar\text{-}cooling} = \frac{Q_e}{Q_{solar}} \qquad \text{Equation (2.5)}$$

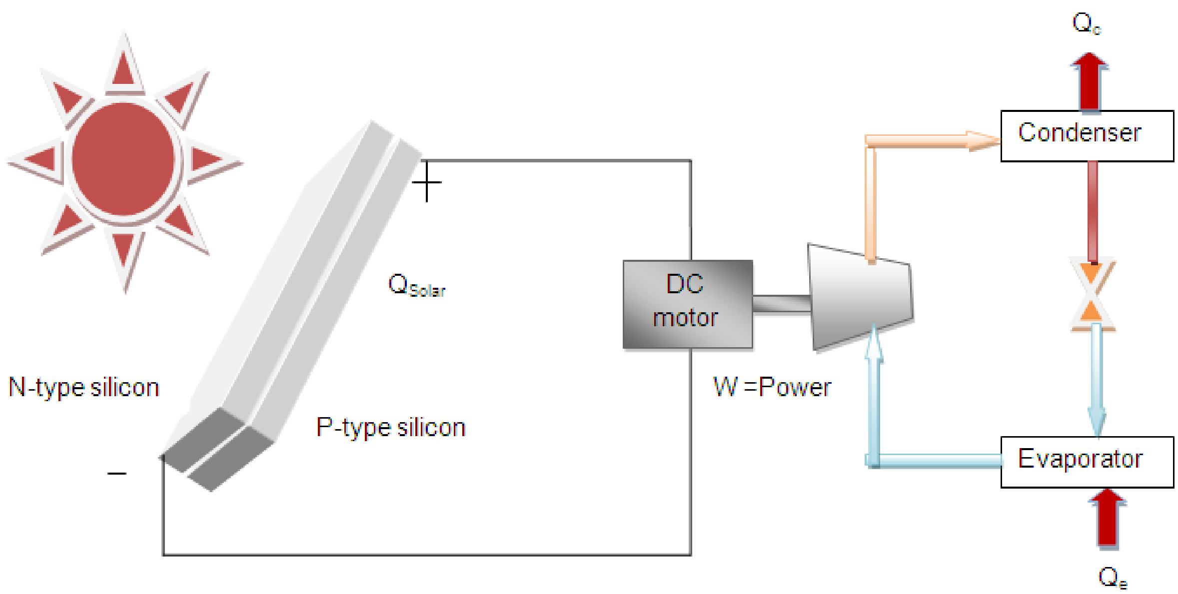


Figure 2.5: PV powered vapor compression system

Adapted from Kim &Infante, 2008

Solar electric vapor compression system is simple and convenient to set up and does not require a lot of service work. Solar electric refrigeration units are available on the market in standard packages with the COPs ranging from 1.1 to 3.3. These units offer a variety of evaporator temperatures comprised between –5ºC to +15ºC and condenser temperatures comprised between 45ºC to 61ºC (Rudischer*et al.,*2005).

However, the use of solar electric vapor compressor poses a twofold problem:

- Firstly, the fact that solar energy supply is not uniform throughout the whole day makes it difficult to rely on PV cells only. Another means such as the use of back up battery or the use of a mixed solar-electric grid to compensate the shortage in power observed in the solar power supply.
- Secondly, solar electric refrigeration systems still have to prove their worth on the market with regards to the cost. So far, the prices of PV cells are so high that they cannot compete with other solar refrigeration systems namely the thermally driven ones.

2.4.4.2 Thermoelectric cooling technology

Thermoelectric cooling (TEC) consists of semiconducting materials supplied by means of electrical power in order to provide the cooling effect. In the context of this project, solar generated power would be considered to supply the thermoelectric material. TEC technology relies on the semiconducting material such as Bismuth Telluride ($BiTe_3$) and Antimony Telluride (Sb_2Te_3) alloys. Thermoelectric cooling technology offers advantages over any other cooling technology: There are no moving parts in the system, neithera refrigerant. It is a kind of compact system that finds applicationsin electronic chip cooling, in portable refrigeration, satellites (especially small ones) and any other applications where the size of the object to be cooled is subjected to limitations. Nevertheless, thermoelectric cooling technology has got a setback when it comes to the COP. The COPs obtainable in thermoelectric cooling systems are as low as to range between 0.3 and 0.6 (Kim &Infante, 2008).

The working principle of a thermoelectric cooling device relies in the Peltier effect. The Peltier device pumps the heat from one side to another side of the device in its solid state when connected to an electrical source of power. Therefore, the direction of the heat transfer depends upon the direction of the current. The hotter side attached to the heat sink while the cooler side is brought to the room temperature. The device itself consists of a combination of the P-N junction pairs. Both layers N and P are doped in such a way that they cannot form a perfect lattice when N and P are in a conduction mode. The doped N layer has got more than the required electrons to form a perfect lattice whilst the N layer has got more than the required holes. The extra electrons or holes are the carriers that move heat when a source of electricity is applied to the PN junction (Ferrotec, 2013). The amount of heat transferred is a function of the amount of the current circulating across the junction and of thermal conditions on either side of the cooling device. For a better cooling effect, many PN junctions or thermoelectric couples are assembled in series. The working principle can be deeply mastered through the understanding of the heat transfer concept.

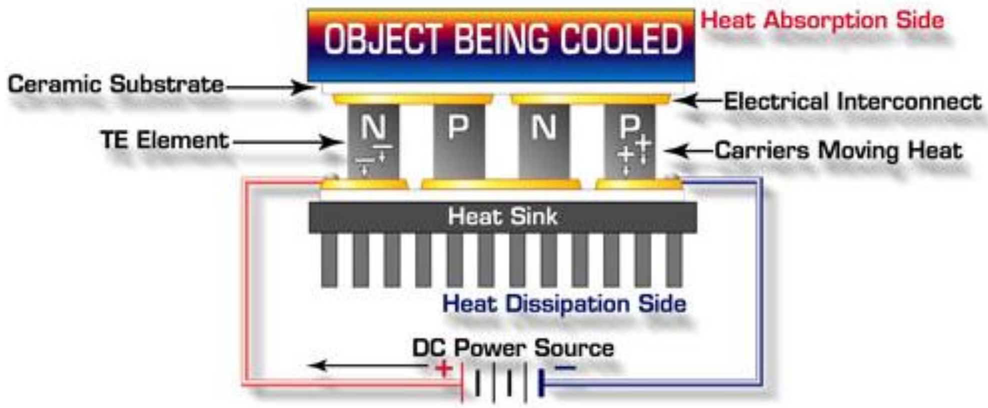


Figure 2.6: Thermoelectric device arrangement (Adapted from ferrotec, 2013)

2.4.4.3 Heat transfer concept

The heat transfer concept can be understood as thermal energy in transit under the effect of spatial temperature gradients. There are three modes of heat transfer namely: i) The conduction, ii) The convection and iii) The thermal radiation.

Conduction can be defined as the heat transfer in a stationary medium under temperature gradients. Deeply, conduction is more authored by a molecular and atomic activity within a substance. Conduction can be seen as the transfer of energy that takes place from the more energetic particles of a substance to the less energetic ones. In terms of energy, higher molecular energies correspond to higher temperatures and lower molecular energies correspond to the lower temperatures in a substance. The transfer of energy occurs when high neighboring molecules collide, thus the heat being transferred from the more energetic to the less energetic particles. Again by going deep into the structure of the matter, the smallest particle is the atom composed by a nucleus and electrons. The latter are in fact the moving particles in the matter's structure. Thus they can carry current and heat at the same time in the direction determined by the polarity of the power source applied. The random collisions of energetic particles (electrons) enhance the heat transfer in the direction from higher to lower temperatures. The heat transfer depends upon the matter's state. In the liquid state matters, the molecules are a bit spaced such that molecular collisions are likely to occur. In solid state matter, the atomic motions are responsible of heat transfer to the lattice waves. In terms of electric conduction, good conductors of electricity transfer heat energy via the transitional motion of the free electrons. The non-conducting matters transfer heat through the lattice waves.

To determine the amount of energy transferred per unit of area, there is a mathematical model also known as Fourier's law (Soukhatme, 2005:349). In the case of heat conduction, this model is also called the rate equation. Equations (2.6 and 2.7)

$q_x^{''}$: The heat flux is the rate in the direction x per unit area and it is proportional to gradient $\frac{dT}{dx}$.

k is the transport property or the thermal conductivity [W/m.K]. k is the characteristic of the wall material.

The (-) sign is due to the fact that heat transfer occurs in the direction of decreasing temperature gradients.

In case the heat transfer is taking place in a linear material, the rate equation can be simplified as follows:

$$\frac{dT}{dx} = \frac{T_2 - T_1}{L} \qquad \text{Equation (2.6)}$$

$$q_x^{''} = \frac{T_2 - T_1}{L} \qquad \text{Equation (2.7)}$$

Convection can basically be understood as the transfer of heat energy taking place between a surface and a moving fluid when the two are at different temperatures. But convection normally happens while the conduction is going on as well. The bulk fluid motion transports an aggregate of molecules interacting between themselves. The resulting energy transfer can be viewed as the superposition of both the heat transfer by random molecules motion and the heat transfer by the bulk fluid motion. The convection is also designated due to this dual heat energy transfer.

Thermal radiation is a heat energy transfer whereby surfaces of finite temperature emit energy in the form of electromagnetic waves. Without of an interfering medium radiation can take place between two surfaces at different temperatures.

2.4.4.4 Stirling cooling technology

Solar panels can be used to drive a Stirling refrigeration cycle. A Stirling cycle working principle and efficiency are the same as the Carnot's cycle (Kim & Infante, 2008). A stirling cycle is a thermodynamic cycle that involves a stirling engine, the invention of Reverend Dr. Robert Stirling in 1816. The stirling cycle is reversible as it can provide a heating or cooling when a mechanical power is supplied to run it. With the stirling cooling, freezing temperatures can be achieved. A Stirling engine is comprised of a free piston and a cylinder. The mechanical power required for compression and expansion can be provided with the help of an electrical motor supplied via solar cells. As in the case of vapor compression cycle, the solar radiation will be converted in electrical power.

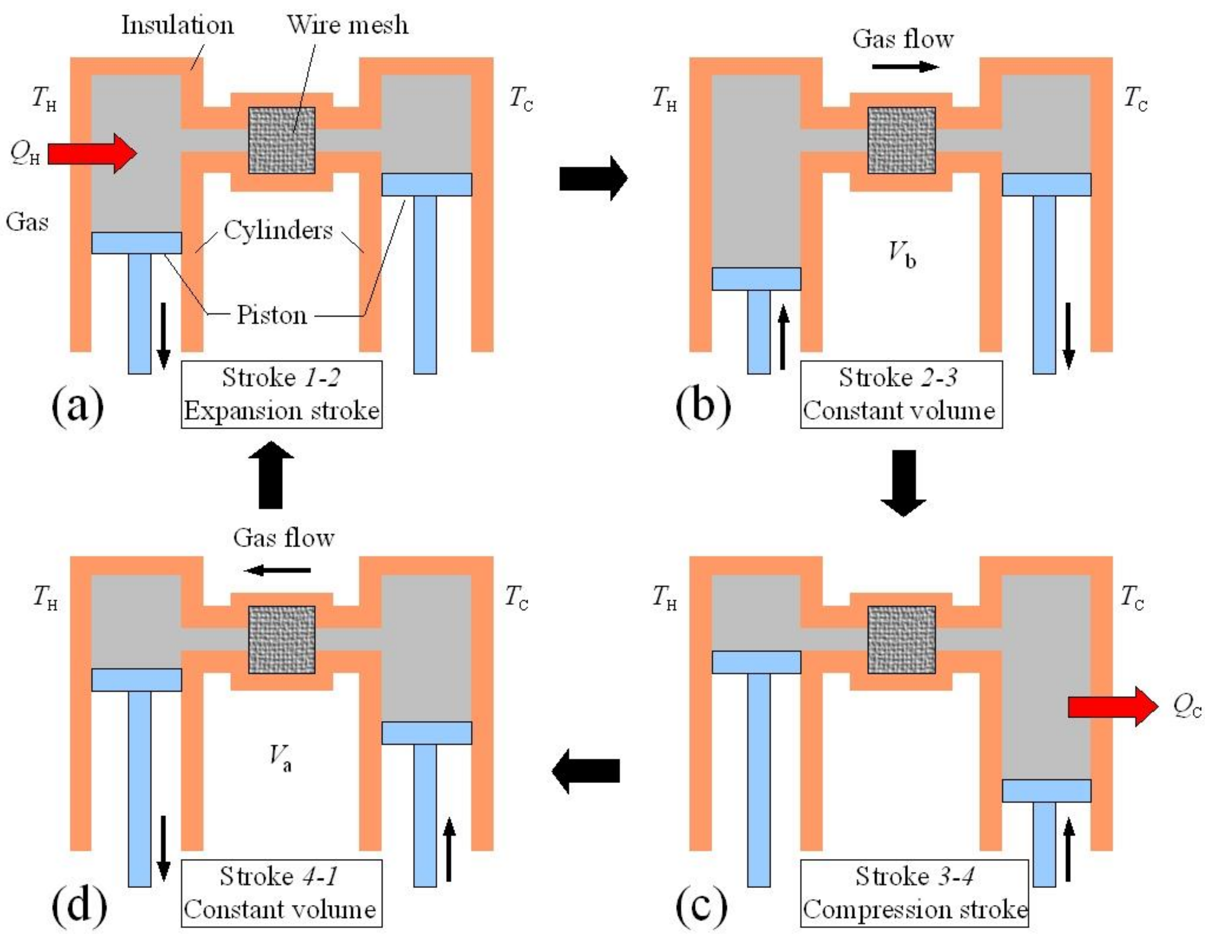


Figure 2.7: Schematic diagram for a Stirling refrigeration cycle (Kribus, 2002)

However, Stirling refrigeration engines are not as efficient as the vapor compression cycle. Their typical low COP (0.8) makes the Stirling engines not convenient for air conditioning applications. The cold side temperatures are estimated to -19.1ºC whereas the hot temperatures range between 28ºC to 30ºC. The low COP is mainly due to the poor heat transfer between the refrigerants, the Helium, and the ambient (Kribus, 2002).

2.4.4.5 Thermo acoustic refrigeration technology

Thermo acoustic refrigeration provides the cooling effect with the help of acoustic waves. With the action of the acoustic waves, the heat gets moved from ambient low temperature medium to the ambient temperature medium. In its propagation, the sound transfers the kinetic energy among air molecules through compression and expansion. During the compression, the heat is transferred between air molecules whereas during the expansion the cold effect is observed in the air molecules. To a further extent, heat is transferred between to reservoirs at different temperatures. The COP of thermo acoustic refrigerators is comparable to that of the Stirling refrigerators (0.8) and is of course lower than the COP of the vapor compressor cooling systems. The temperatures in the heat exchangers are 33.9ºC and -24.6ºC. Like thermoelectric cooling, thermo acoustic offers the advantage of not having moving parts, and of being self-contained. However, due to the low power density, large cooling power cannot be achieved using thermo acoustic machines.

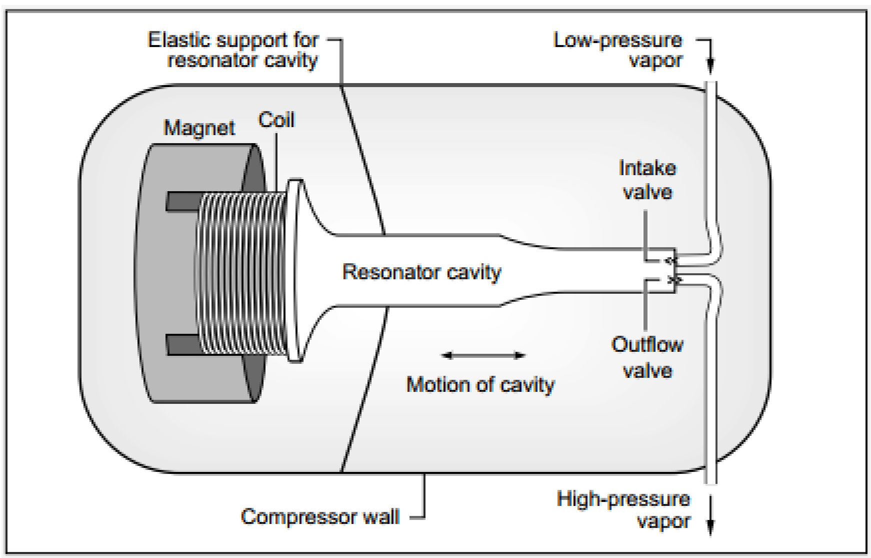


Figure 2.8: The sonic compressor (Los Alamos Science, 1993)

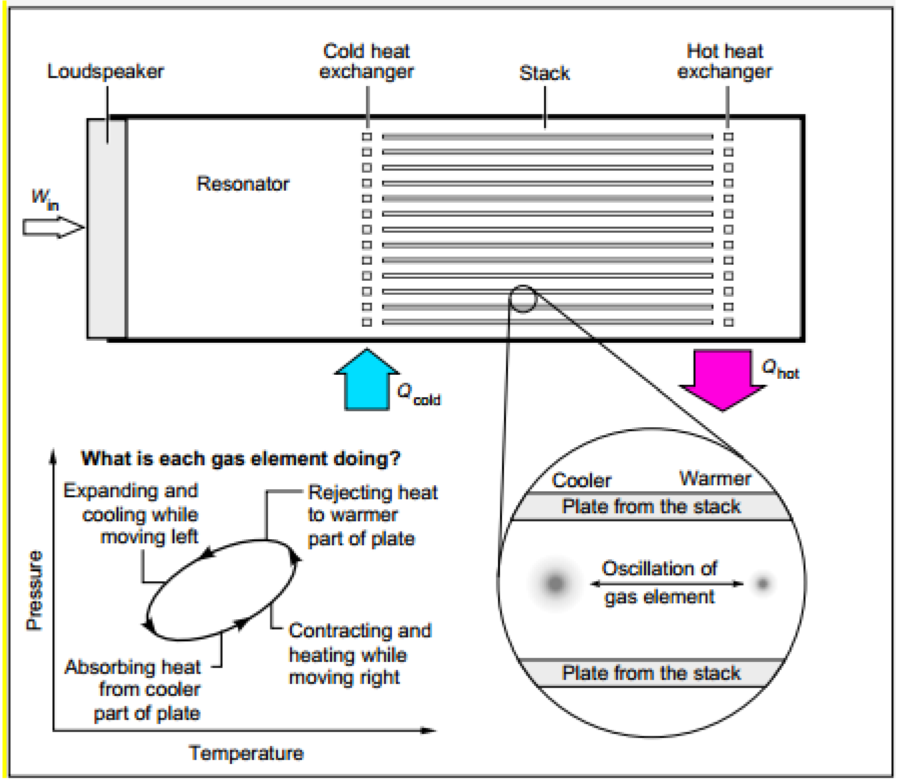


Figure 2.9: The schematic of operation mode of the thermo acoustic cooling (Los Alamos science, 1993).

2.4.4.6 Magnetic cooling

In the magnetic cooling, the cooling effect occurs when of a material changes the temperature due to the change of the magnetic field. This effect is also known as magneto caloric effect (MCE). Magnetic cooling is known for high COP order of 3.0 (Kim & Infante, 2008). Magnetic refrigeration systems using permanent magnetic room temperature have been developed and (Gschneider, 2001), with the COP described above, they have proven to be better than the vapor compressor refrigeration systems. However, the high cost of magnetic material (Fischer &Labinov, 2000) makes magnetic cooling not popular as compared to the vapor compression cooling.

2.4.4.7 Electrochemical cooling

The electrochemical cooling is based on thermal effects that occur during a reversible electrochemical reaction. This kind of reaction normally takes place in an electrochemical cell whereby heat is released when a cell is supplied with a positive voltage. The cooling effect is obtained when the electrochemical cell is supplied with a negative voltage. In this case the cell behaves differently and absorbs the heat from the surroundings (Gerlach & Newell, 2003).

Electrochemical cooling technology is still under thorough investigation with regards to its implementation for refrigeration applications.

2.4.4.8 Ejector refrigeration

The ejector refrigeration has been mostly used for the cooling of buildings and trains. So far, their performance is low when compared to the vapor compression refrigeration which enables COPs as high as 3.3 with the generator's temperatures ranging from 85^0C to 95^0C. At these same temperatures, the ejector refrigeration's COPs are as low as a tenth of the vapor compressor's ones (Murthy *et al.*, 1991; Nguyen *et al.*, 2001). The ejector refrigeration system is viewed as simple in terms of development. However, the COP is still a handicap as temperatures as high as 200^0C are required to achieve satisfactory results. Therefore, ejector cooling systems are far from being competitive in the pool of refrigeration technologies.

2.4.5 Solar thermally driven cooling technologies

Solar thermally driven cooling technologies are those run on a solar thermal energy. Thermal or work driven cooling systems are supplied in heat via solar thermal collectors there are two main types of solar collectors, namely the flat plate solar collectors and the evacuated solar collectors (Figure 2.10).Solar collector convert solar radiation into thermal energy useful to drive a thermo mechanical cycle, an absorption refrigeration cycle, an adsorption cycle, a chemical reaction cycle, a desiccant refrigeration cycle, or rejection refrigeration cycle. The conversion from solar to thermal energy is operated with the help of a fluid flowing through the solar collector such as water, air, oil and antifreeze mixture (Salgado & Rodriguez, 2008:18)Thermally driven cooling systems suit the better the air conditioning and the cooling of food stuffs and vaccines. Temperatures ranging between 0ºC and 25ºC can be attained. Among the refrigeration cycles used in thermal driven systems, the absorption refrigeration cycle offers better performance than the others (Mittal *et al*., 2005). Solar thermal collectors are commonly used to heat water in summer to save the electrical power allocated to the geyser and to the other heating appliances.

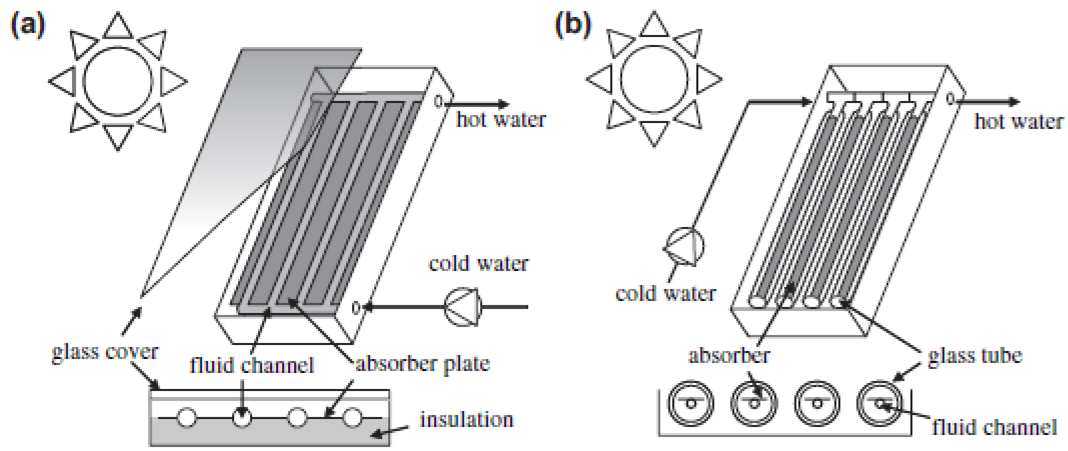


Figure 2.10 a) Schematics: flat plate solar collector b) evacuated solar collector (Adapted from Kim &Infante, 2008).

The flat plate collectors (FPC) are commonly used for domestic applications whilst evacuated or tube collectors (ETC) are best suited for industrial applications where processes can occur at temperatures as high as 200ºC (Duffie& Beckman, 2006; Eicker, 2003). The FPC consists of a flat metal covered by a transparent glass. It is known to work at lower temperatures and to be more heat loser than the ETC. Solar collectors' efficiency is a function of their working temperatures (Kim &Infante, 2008). The efficiency of thermal collectors is determined by the ratio of the amount of solar radiation received by a solar collector (Q_s) over the amount of heat converted. In the case of a thermo electric cooling system (Q_{EM}), this amount of heat converted is the one to be supplied to the mechanical engine to drive it. The amount of the direct solar radiation received by a solar collector is determined by the incident solar radiation per unit area (I_P [kW/m^2]) and to the area of the solar collector.

$$\eta_{sol\text{-}heat} = \frac{Q_g}{Q_s} = \frac{Q_g}{I_P A_s} \qquad \text{Equation (2.8)}$$

2.4.5.1 Thermo mechanical cooling

In thermo mechanical cooling, a heat engine converts the heat energy from the solar collectors into a mechanical energy, which in turn is used to run a mechanical vapor compression unit (Figure 2.11).

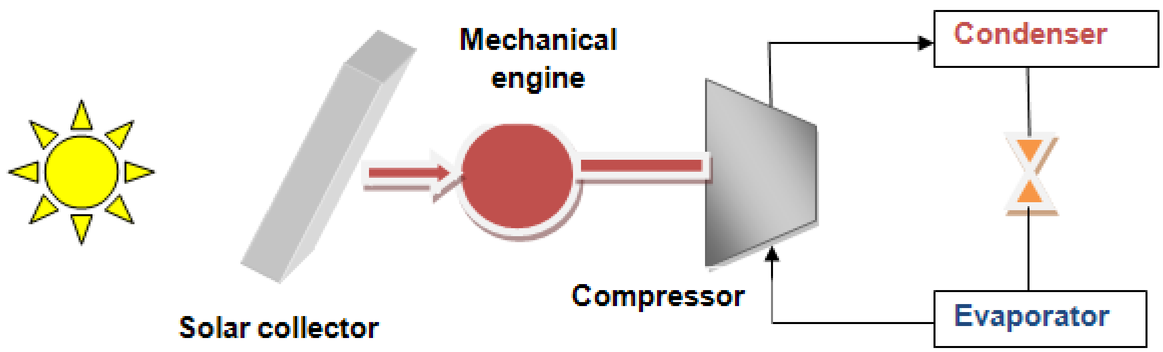


Figure 2.11: Schematic for a thermo mechanical cycle

Rankine and Stirling engine have been used as thermo mechanical engine that are powered via solar thermal energy from the solar collectors. The efficiency of the overall system will depends upon the efficiency of the solar collectors in terms of converting solar radiation into thermal energy, and upon the efficiency of the mechanical engine in terms of converting mechanical energy into cooling energy.

2.4.6 Absorption cooling technology

The absorption cooling effect is provided by an absorption chiller. The absorption chiller is driven by heat energy in the form of hot water, steam or combustion. In summer times, solar energy is used to drive the absorption chillers. The cooling effect is provided in an absorption cycle whereby a refrigerant and an absorbent are used to create high pressures in the generator. In an absorption cooling system, water is used as a refrigerant and Lithium Bromide (Li-Br) is used as an absorbent.

2.4.6.1 Single effect solar absorption cooling system

A single effect absorption cooling cycle comprises the following four main components: A generator, a condenser, an evaporator and an absorber (Li &Sumathy, 2000; Ahmed, 2011) (Figure 2.15). The cycle starts in the absorber where the dilute solution is pumped from the absorber to the generator. High temperatures and high pressures result in the evaporation of the refrigerant and the recovery of the strong solution of Lithium Bromide. The strong solution collects itself at the bottom of the collector whilst the refrigerant vapors, at high pressure, are propelled to the condenser. In the condenser, these vapors release their heat energy to the chilling water surrounding the condenser. From the condenser, the vapors are released with the help of a metering device also known as an expansion device. The vapors undergo a pressure drop in the expansion process and are drawn to the evaporator due to the vacuum created during the pumping of the dilute solution to the generator. The cooling effect is obtained through the passage of cooled low pressure vapors that absorbs the heat of the space to be cooled. The cooled vapors are drawn to the bottom of the absorber to be absorbed into the strong solution of Lithium Bromide and the cycle restarts. This cycle is known as the single effect refrigeration cycle. Absorption cooling system can be used either for air conditioning applications with the chilled water's temperature above 5ºC or for refrigeration purposes where the chilled water's temperature is below 5ºC. A water/lithium bromide solution (H_2O/LiBr) is suitable for the air conditioning applications, whilst the ammonium/water solution (NH_3/H_2O) is suitable for refrigeration applications. Typical absorption machine can provide the cooling power of order a hundred kilowatts (Ahmed, 2011).

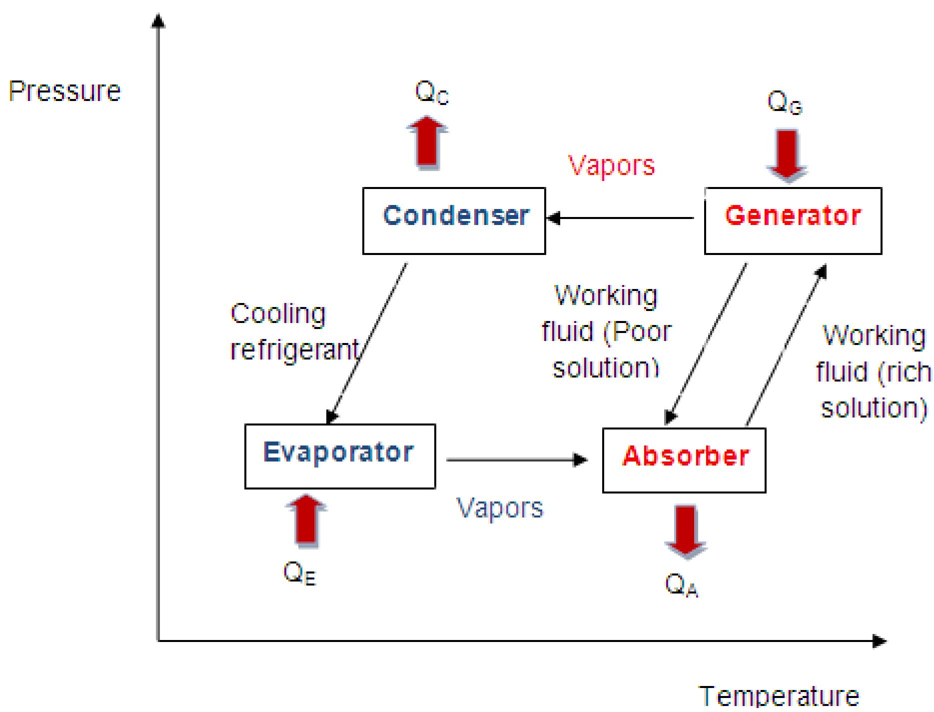


Figure 2.12: Pressure and temperature in absorption cycle

From the diagram in Figure 2.12, the sorption refrigeration system goes through different temperatures and pressures. This corroborates the existence of three main levels of temperatures in a sorption cycle (Eco building, 2007) (Figure 2.13). There are a high level temperature at which the driving heat is absorbed (absorber and generator), a low temperature level at which the heat is absorbed from the air-conditioned space to the evaporator and a medium temperature level at which the heat is rejected from the condenser. In terms of pressure, water vapors are at low pressure in the evaporator and in the absorber. The pressure goes high in the generator after the water/Lithium bromide diluted solution reacts at very high temperatures. The vapors' pressure increases in the generator and the condenser. It only becomes low again after the expansion device.

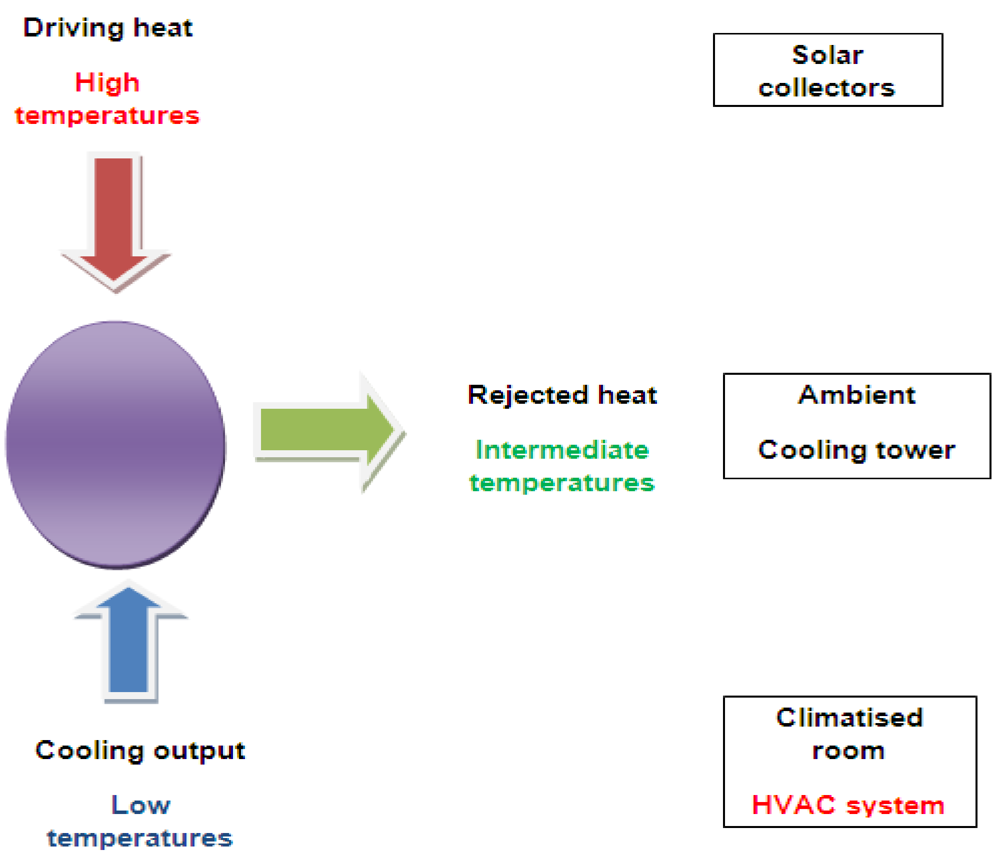


Figure 2.13:Levels of temperature in a sorption chiller

(Adapted from Eco building,2007)

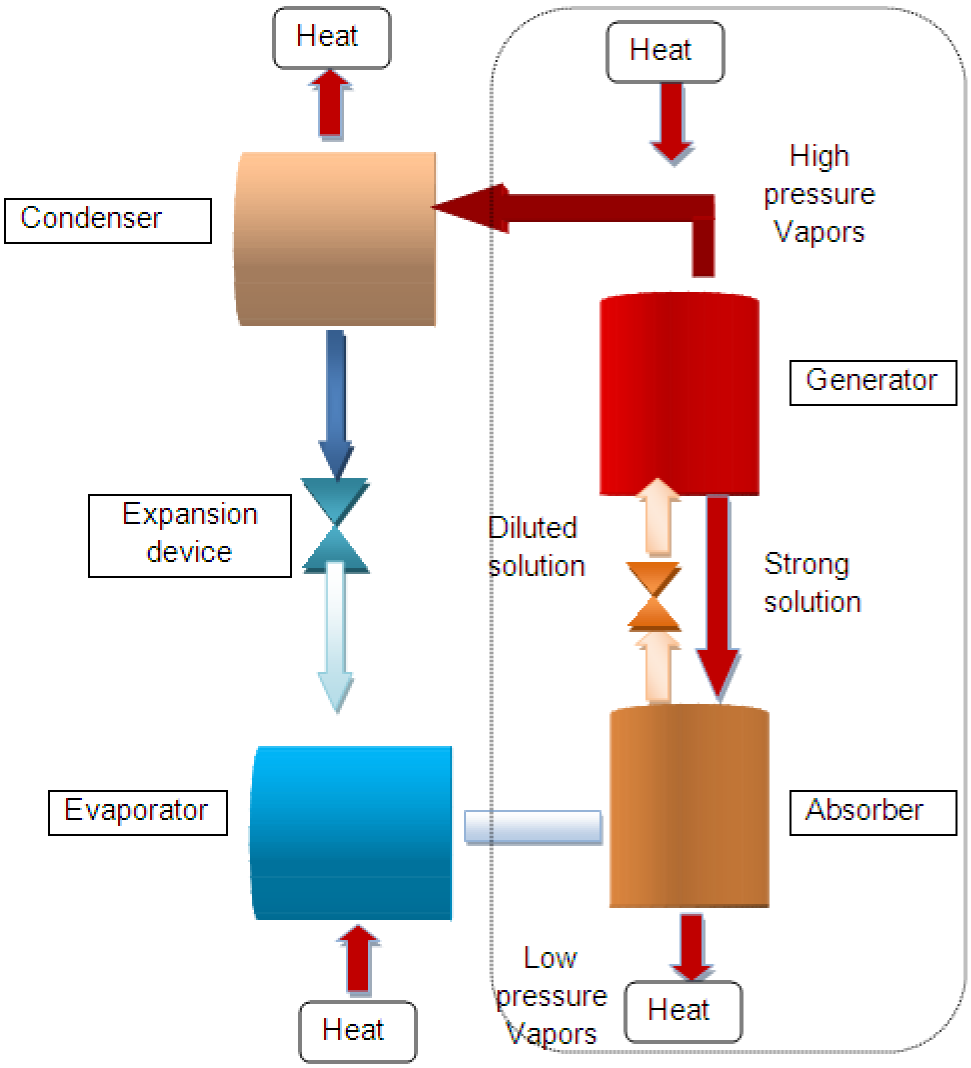


Figure 2.14: Absorption cooling (Adapted from Lim *et al.,* 2009).

Comparing the two technologies, compressor based and sorption based, the electromechanical compressor's work is performed by the combination of the absorber and the generator. The absorption chiller just needs a pump running on little electrical power to move the Lithium bromide water solution from the absorber to the generator. Moreover, the absorption chiller requires the heat energy at the generator stage to preheat the strong solution of Lithium bromide.

Figure 2.15: Example of Single effect absorption cooling machine

(Adapted from Li &Sumathy, 2000)

2.4.6.2 Double effect solar absorption cooling systems

A double effect solar cooling system is an upgrade of the single effect solar absorption cooling system. On top of the components of the single effect type, the double effect has a high pressure generator, a secondary heat exchanger and heat recovery unit (Dai, 1997).The double effect helps reduce the temperature demands of order 73ºC required in the single effect absorption chillers by circulating the weak solution in the additional components.

2.4.6.3 Two stage solar absorption cooling systems

A two stage solar absorption cooling system is used to circumvent the non-economical aspect encountered in single effect cooling systems with regards to solar collectors. As the cost of solar collectors rises with their ability to deliver high temperatures, it is important to lower the solar collectors cost by using low temperature solar collectors.

2.4.6.4 Adsorption cooling technology

Adsorption cooling systems are thermally driven processes. Therefore, thermal energy required for such cooling systems can be provided by using solar means. Solar collectors are used to behold the adsorbent and to gather the solar radiation and convert it into thermal energy. Like the absorption cooling systems, the adsorption cooling systems comprise the heat exchangers, the condenser and the evaporator (Figure 2.14). The adsorption processes are based on solid or liquid adsorbents that can bind with liquid or gas respectively (Kim & Infante, 2010, Heinz *et al*., 2010; Wang, 2006). The adsorption chiller uses the water as a refrigerant. The water vaporizes at room temperature whereby it extracts heat from the surroundings and thus provides a cooling effect.

The adsorption processes can be broken down as follows (Heinz *et al*., 2010; Wang & Oliveira, 2005; Bakker & de Boer, 2010): during the day, the solar radiation heats up the solar collector. The adsorbent releases the adsorbed water producing high pressure vapors that are sent to the condenser by virtue of pressure and heat transfer. From the condenser, the low pressure condensed water vapors are admitted to the evaporator via a metered valve where it is collected. During the night, the solar collector cools down and become ready to adsorb water again. Water moves from the evaporator to the colder solar collector, thus dropping the chilling chamber's temperature.

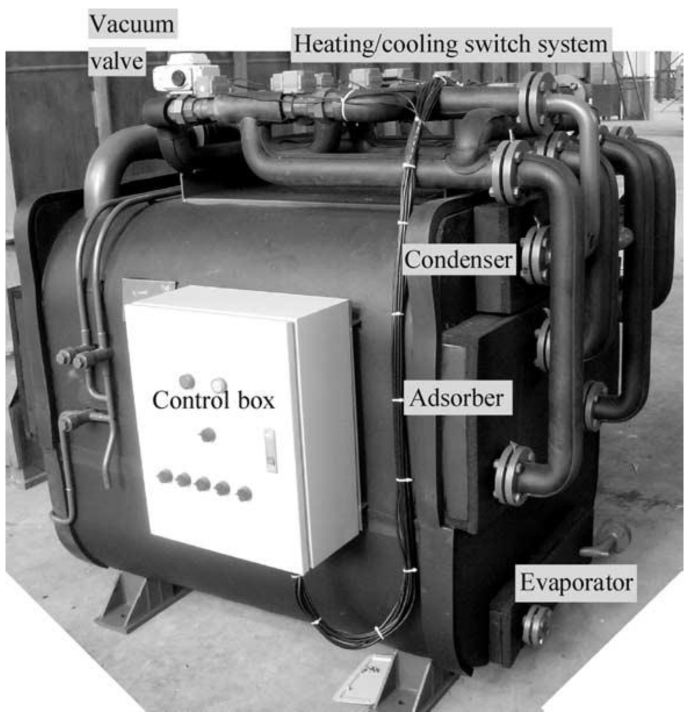


Figure 2.16: Adsorption engine (Adapted from Wang *et al.*, 2005)

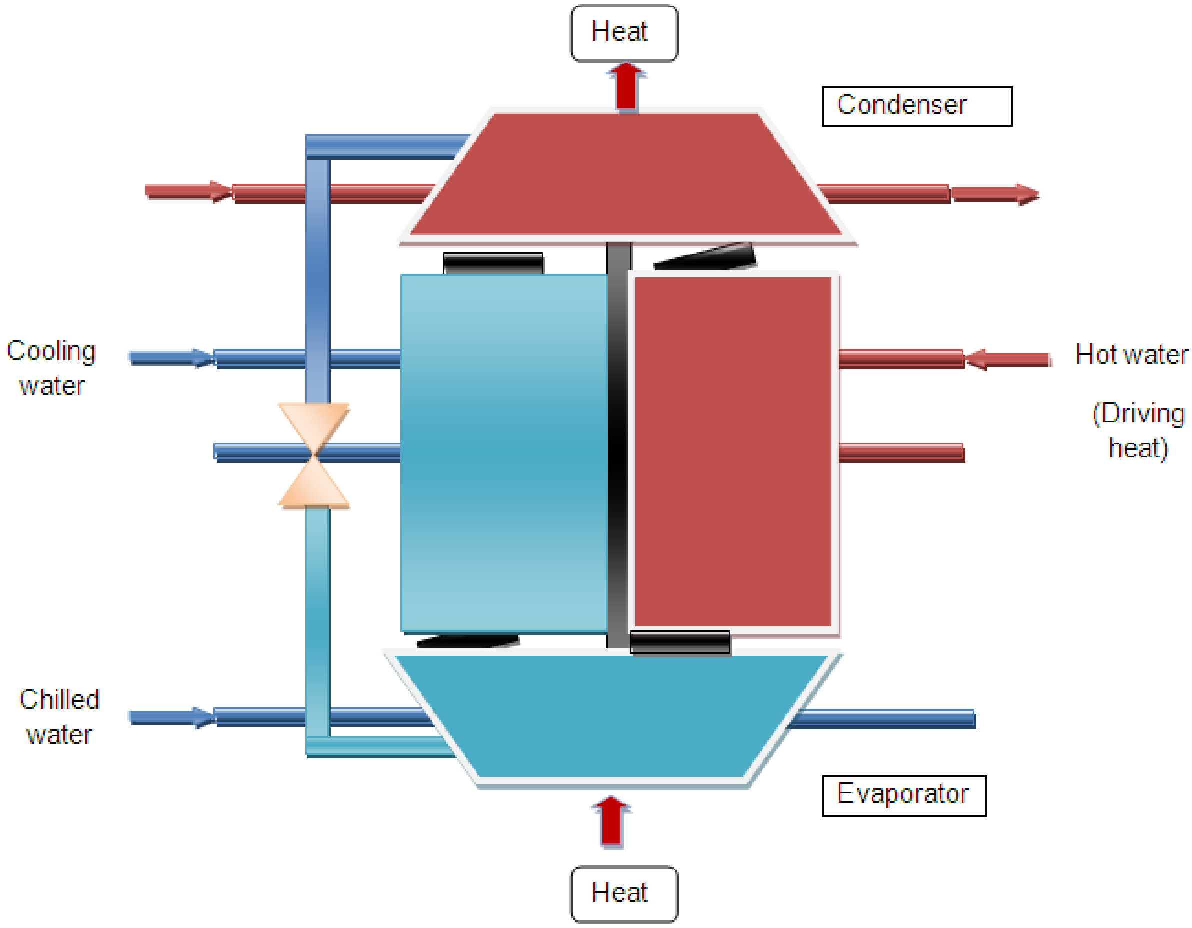


Figure 2.17: Schematic principle of an adsorption chiller

(Adapted from Dutil and Rousse, n.d.)

2.4.6.5 Desiccant cooling

The desiccant cooling technology is an open loop system. It consists of two processes: the adsorptive dehumidification and the evaporative cooling (Figure 4.9). For the adsorptive process, the water vapor contained in the air is deposited on a porous material with a large internal surface. The dehumidification is done before the evaporation, and this increases the effectiveness of the evaporation in such a way that the temperatures needed for desorption range from 55ºC to 90ºC, temperatures achievable with the help of a solar collector (Dutil& Rousse, n.d). Desorption is a phenomenon whereby a substance is released from or through a surface. Typical desiccant systems use a rotating wheel for a continuous removal of the moisture from the air.

2.4.6.6 The cooling process in desiccant systems

The cooling process starts in the dehumidifier. In its rotation, the desiccant wheel placed across the entrance and the exit of the air stream captures the moisture from the room or ambient air. The moisture is captured by the concentrated solution and then becomes diluted while the cool and dry air passes through the cooler device and channeled to the air-conditioned space. The diluted solution is further cooled by the cooling coil (connected to the solar collectors) and is deposited on the bottom of the dehumidifier. Afterwards, the diluted solution is taken to the top of the regenerator and sprayed on heating coils and ambient air is blown inside the regenerator. The desiccant is regenerated and goes to the bottom of the regenerator, while the hot air is exited. The concentrated solution is then channeled to the heat exchanger and then to dehumidifier and the cycle restarts.

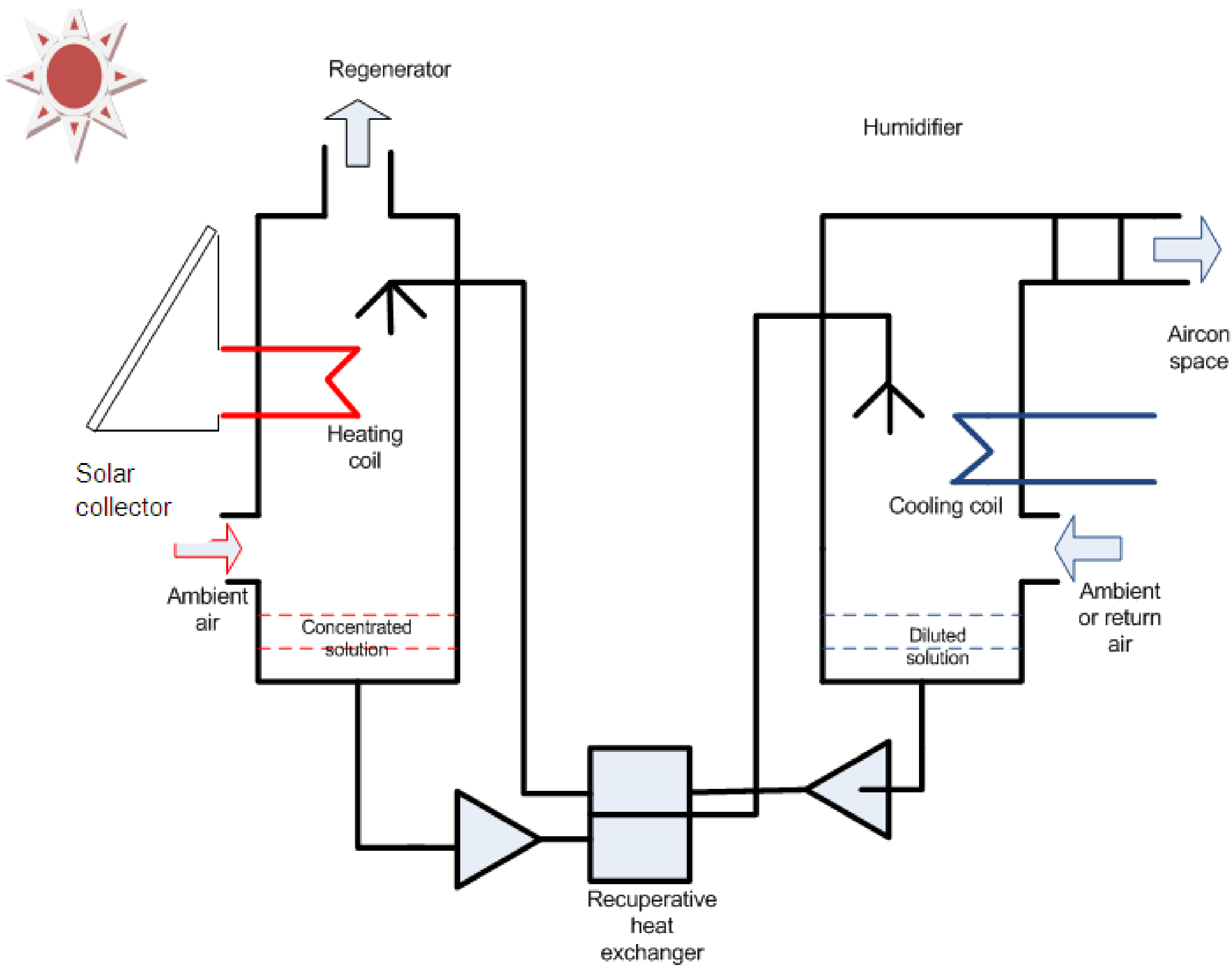


Figure 2.18: Schematic diagram for a solid desiccant cooling system

(Adapted from Kim and Infante, 2008)

2.5 Summary

The cooling technologies overviewed in the literature survey are of two main types: passive and active. Passive technologies commonly find application in the buildings' air conditioning by using natural means and some material properties. In the context of the mobile satellite ground station, the thin films could be used on the door and window glasses of the mobile ground station in order tominimize thermal infra-red radiation whilst allowing the daylight inside the structure hosting the ground station and the mission operators. White paint is recommended for the body of the moveable unit whereby they will be reflecting away the long wavelengths including the NIR carrying thermal energy. For the active technologies, the literature survey indicates that they suit the air conditioning, the food storage and the freezing. They are also convenient for the cooling of electronic devices. Also solar powered cooling techniques have been pointed out to be clean and to comply with the applications to the mobile ground station. A detailed comparison between them shall be elaborated in the next chapter.

CHAPTER THREE: CONSTRAINTS AND SYSTEM REQUIREMENTS

3.1 Introduction

This chapter of the thesis contains the constraints and limitations taken into consideration towards the system development, the quantitative study of thermal noise effects on the signal's quality and on the amplifier from which the system requirements were elaborated.

3.2 Design considerations and constraints

The system requirement has looked at the low noise amplifier and at the truck containing the ground station itself. Within the FSATI satellite system there are two LNAs, one at the cubeSat ZACUBE-1 and another one at the ground station. The two LNAs are known as Advanced Receiver Research (Figure 3.1).

Figure 3.1: Advanced receiver research (Adapted from Ar[2] communications)

At the ground station, there is the MSP 432 VDG-160 while the MSP 144 VDG-160 is fitted on the satellite. For this research project only the LNA located at the ground station was focused on. The truck (Figure 3.2)containing the receive equipments was looked at as well in terms of cooling since on board of it there would be mission operators who will definitely need comfort temperatures especially in hot summer seasons.

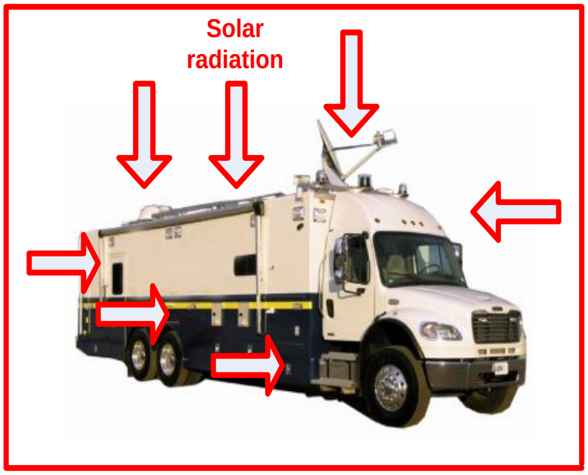


Figure 3.2: Truck for receive equipment and space mission operators

The cooling system development has looked at the overviewed cooling techniques and some considerations were made as follows:

3.2.1 Limitations and constraints

The cooling technologies with regards to mobile ground stations should take into considerations of various restrictions or limitations related to the nature and the mode of operation imposed to the mentioned stations.

3.2.1.1 Practical and economical restrictions

The techniques to be developed to lower the temperatures inside a mobile ground station should be in compliance with the "lightweight" aspect of mobile ground stations. In fact, for practical and economic reasons, the mass of the SMGS must allow easy transport from site to site within reasonable times and with low fuel cost. This can only be achieved by making the mass of the SMGS as low as possible with regards to the cooling system.

3.2.1.2 Structural restrictions

An SMGS must be in compliance with the traffic regulations with regards to its size. Therefore, the cooling systems should not be cumbersome or be shaped so as to dictate sizes beyond the traffic fixed boundaries for vehicles.

3.2.1.3 Power consumption

In terms of power consumption, conventional cooling methods are electrical power reliant to work. In this particular case of study, a mobile ground station should preferably work without any external source of electrical power as it applies to all portable or mobile apparatuses.

Alternatively, if the SMGS has to resort to any source of power, the latter should be of a renewable type.

3.2.1.4 Human and environment concerns

The cooling system to be developed for the mobile satellite ground station must not be harmful to human livings and the environment as traditional techniques used in buildings do. There are diseases sometimes deadly that are encountered in buildings fitted with air conditioning systems. Those diseases include the sick building syndrome, a sickness associated to the living or work environment (Yu *et al*., 2009; Kim &Infante, 2008)

Lastly, the cooling system in perspective should not resort to openings in order to radiate out the heat from the SMGS. The electronics inside the mobile satellite ground station should not be exposed to the effects of bad weather and debris in order to avoid hazard shocks that can cause the spoilage of the electronics.

3.2.2 Thermal noise quantitative study

The cooling system development has also required a prior quantitative study of thermal noise and its effects with regard to the signal quality and the amplifier's life span.The quantitative study of thermal noise was conducted at the front end Low Noise Amplifier of the FSATI's current ground station as to know critical values at which the noise is unacceptable and where the amplifier can be destroyed due to thermal noise. The best way to achieve this study was to use simulation software. In this case LabVIEW 2012 software package was used along with Matlab. A Graphical User interface (GUI) (Figure 3.4) was developed to record the LNA parameters (Table 3.1) and display the values of the noise and the eventual effects. The same logic followed to develop this GUI was used to set the control system for the cooling system.

Table 3.1: LNA parameters

Parameter	Lower limit	Upper limit
Frequency (MHz)	420	450
Noise Figure	0.55	
1 dB compression (dBm)	12	
1 dB BW (MHz)	40	
Supply voltage (V)	10	16
Currents Transmitting mode (mA)	10	
Currents Receiving mode (mA)	200	
Attenuation max(dB)	0.5	
Gain (dB)	16	
Through power (dBm)	52	

3.2.2.1 Interpretation of the LNA parameters

Among the parameters above:

- The bandwidths are directly involved in thermal noise generation
- The1 dB compression of 12 dB is connected to the limit of the noise floor. The 1 dB compression suggests that the acceptable noise floor is of -88dBm. This verifies Pozar (2005 :) who stipulates that the noise floor is comprised within -100dBm and -60dBm.

$$\text{Noise floor} = \left[-100 - (-12)\right] \text{dBm} = -88 \text{ dBm}$$

- The LNA through power of 160 Watts reflects to the maximum power that can be found at the LNA output. In dBm, 160 Watts are equivalent to 52dBm. The input power is supposed not to exceed 36dBm
- The gain of 16dB implies that the output signal is 40 times the output(Appendix 1)

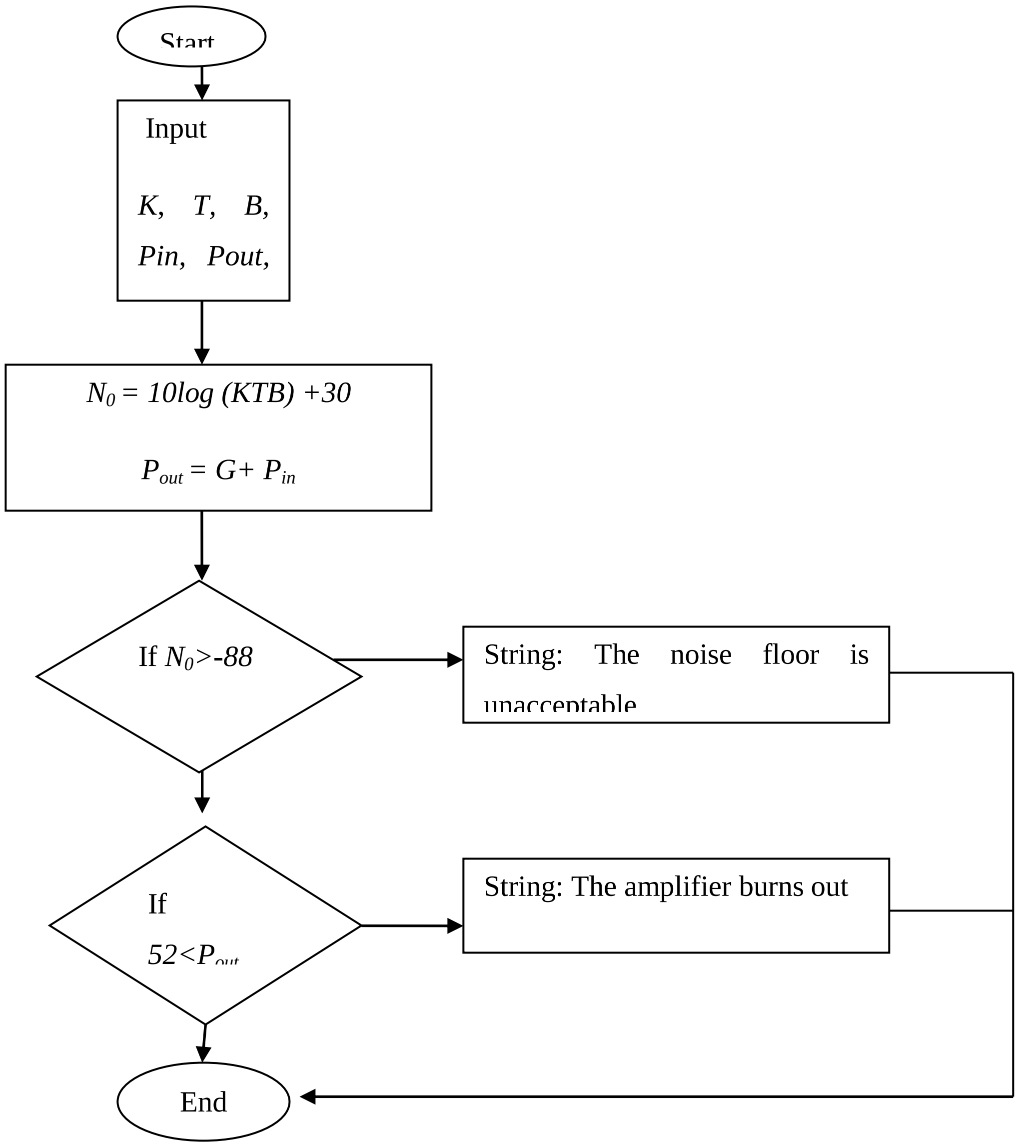


Figure 3.3: Flowchart for the thermal noise effects simulations

3.2.2.2 Simulation of thermal effects on the LNA

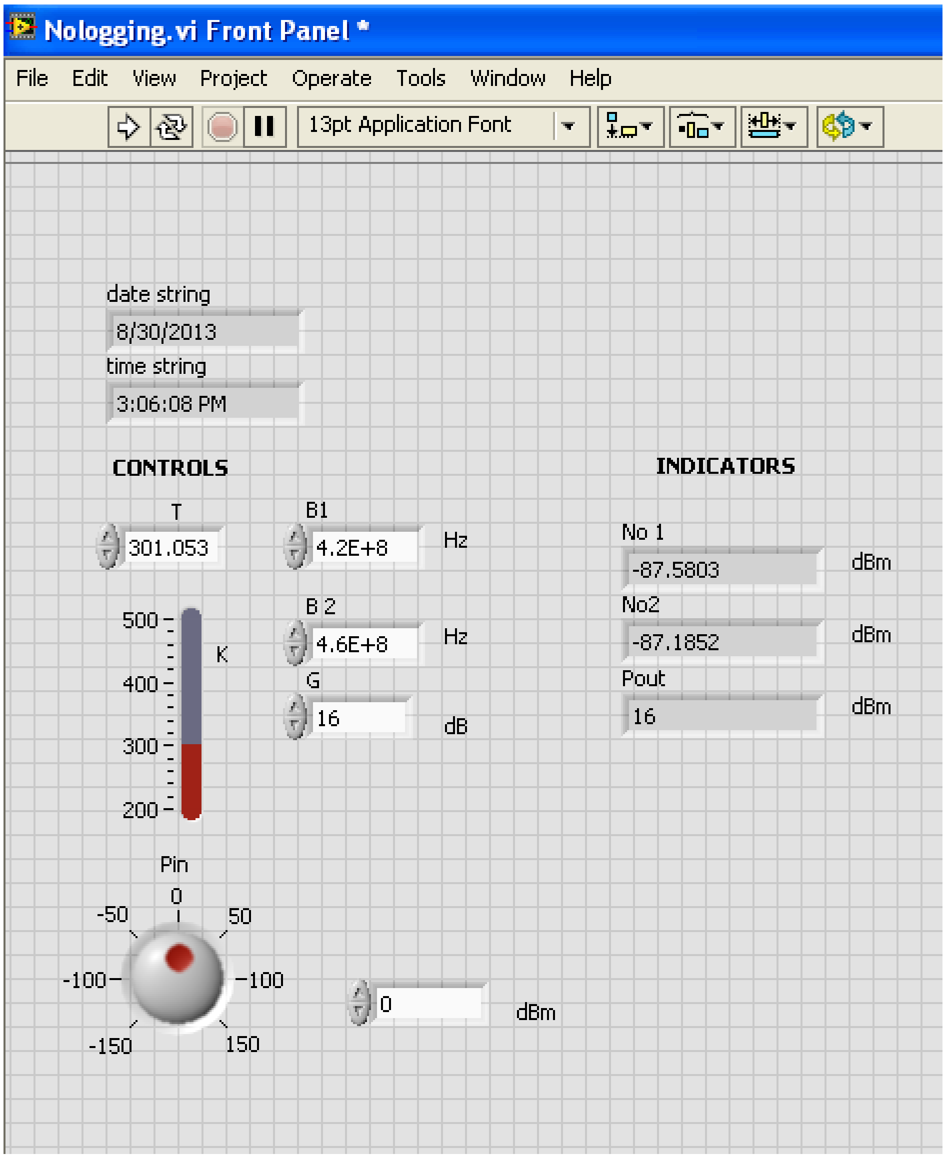


Figure 3.4: The front panel of the GUI.

The GUI comprises two main faces:

- A front panel where the user has the controls and indicators. The controls are the replica of the inputs and the indicators represent the outputs. In the case of the study of the LNA's behavior, the controls' side enables the user to enter the LNA's parameters namely the temperature (T), the lower and upper frequencies of operation (B_1 and B_2 respectively), the gain (G) and the input power (Pin). Some parameters (Temperature and signal input power) which are susceptible to vary in the lifetime of the LNA, have been allowed to input with the help of specific palettes. The indicators' side is meant to display the output results namely the output power, the noise (No_1 and No_2 respectively corresponding to the lower and upper bandwidths. The effect of thermal noise on the LNA is displayed in the form of a string. Strings such as "The noise floor is unacceptable" and "the amplifier burns out" are displayed where applicable.

$$N_o(dBm) = 10\log(KTB) + 30\left[dBm\right] \qquad \text{Equation (3.1)}$$

$$S_o(dBm) = G + S_i(dBm) \qquad \left[dBm\right] \qquad \text{Equation (3.2)}$$

- The block diagram (Appendix 2) is the other face of the GUI whereby Vis are assembled according to the flowchart (figure 3.3)

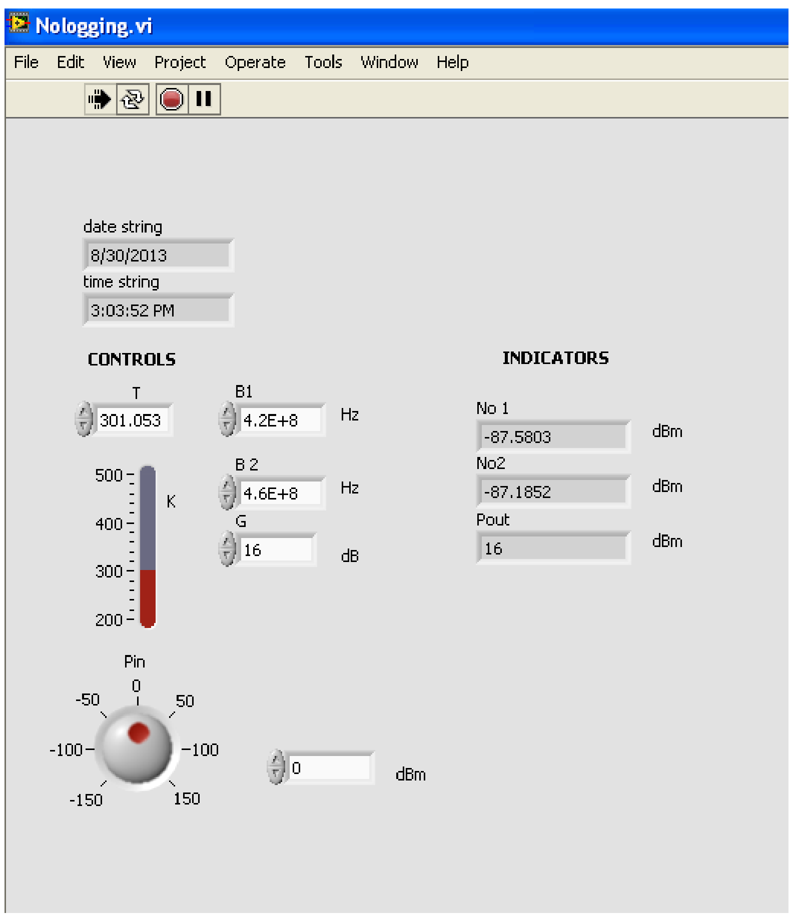


Figure 3.5: Case of the GUI computing thermal noises

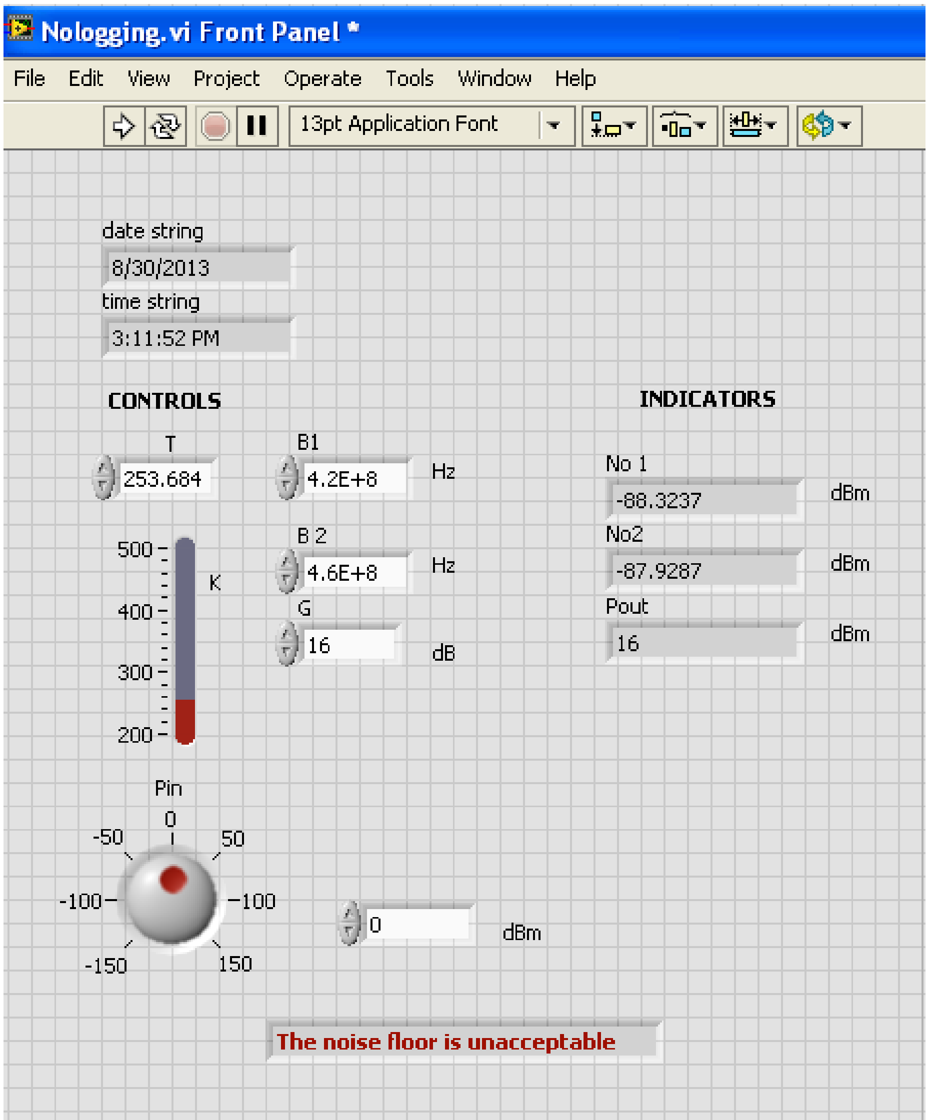


Figure 3.6: Illustration of the case where the noise floor is greater than the acceptable limit.

The noise floor that exceeds the 1 dB compression equivalent to -88dBm is judged to be unacceptable.

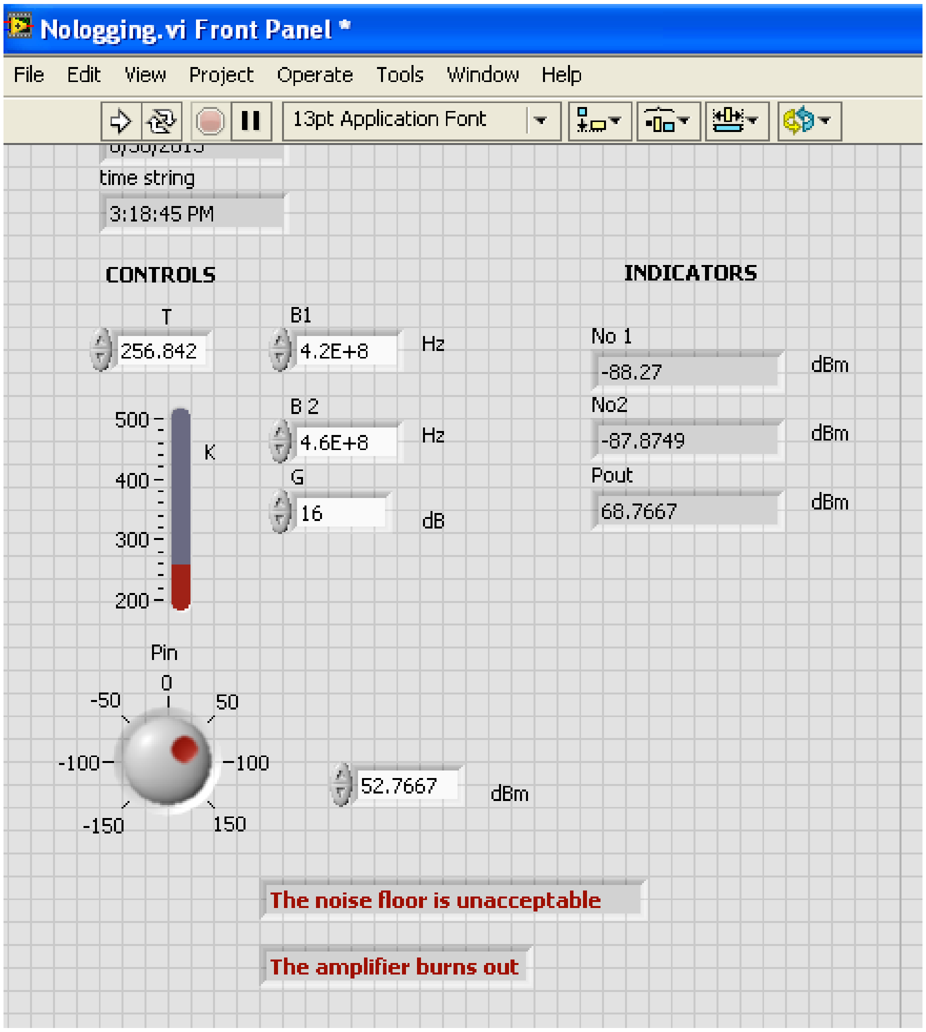


Figure 3.7: Case where the input power is too high

3.2.2.3 Simulation of the dynamic range in virtue of Pozar (2005)

The code used to simulate the behavior of the LNA is in the Appendix 3.

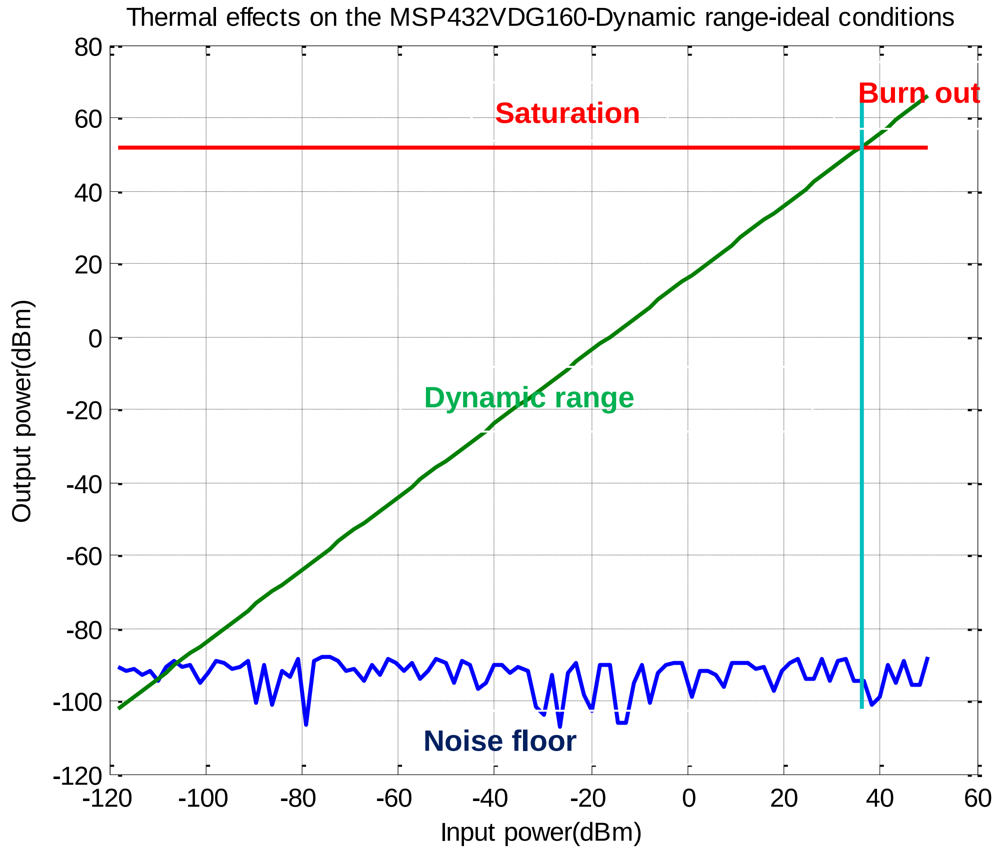
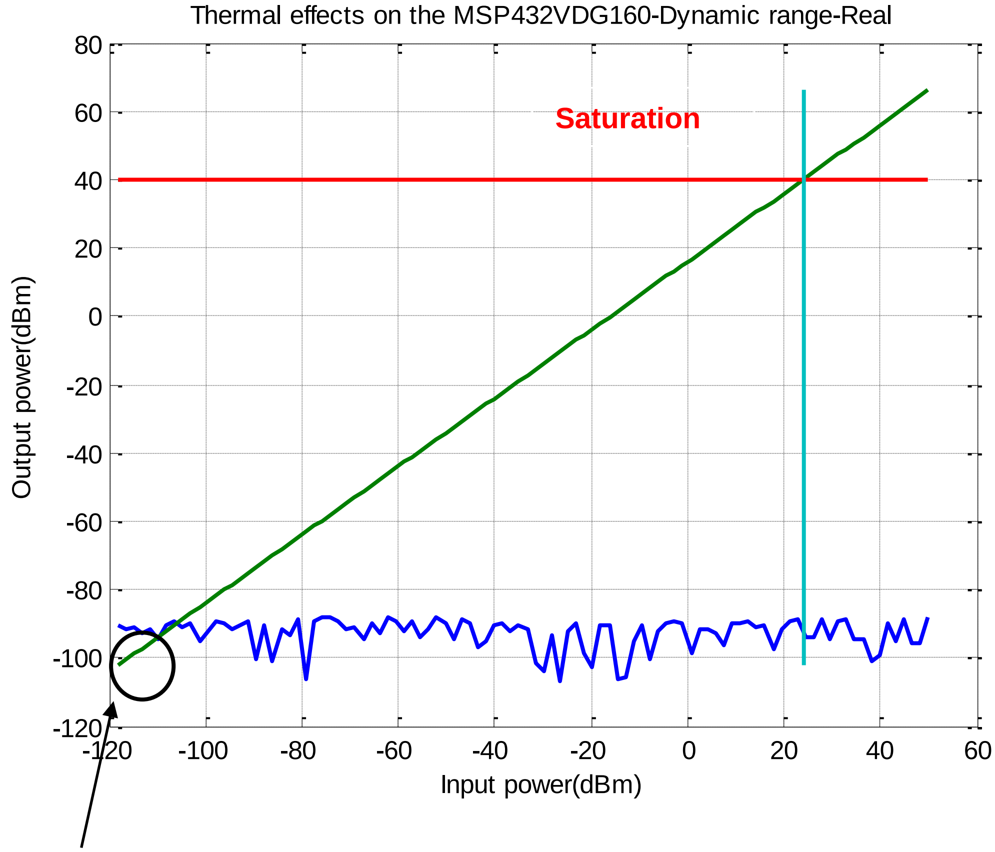


Figure 3.8: Thermal effects and the dynamic range of the LNA in ideal conditions

On this figure 3.8, the output has been simulated in ideal conditions without taking into account the effect of the noise on the output. But in reality, the noise floor adds on the output signal and then the dynamic range finds itself reduced (Figure 3.9). Instead of having the output signal of 52dBm (160W), the output signal will have only 40 dBm (10W) approximately; the rest will be the part of the thermal noise. As a consequence, any input signal greater than 40dBm may lead the LNA to saturation and further to destruction. In terms of the dynamic range, the upper limit of the dynamic range drops from 52dBm to 40dBm. This effect can be alleviated to some extent by the cooled elements (Pozar, 2005).

It is also noteworthy to highlight that the signals of which the output power is below the noise floor will not be sensed. These signals are those having the output below -88dBm. In other words, the input signal powers less than -104dBm will not be sensed. In other words the input signals of which the power is less than 39 nW will not be detected at the output of the LNA as they are immerged underneath the noise floor.



The signal will not be detected

Figure 3.9: The graph of the input versus output signal in real conditions

Regarding the thermal noise quantification, Table 3.2 shows the variation of thermal noise for the lower and the upper frequencies of operation respectively through the range of operation temperatures of the LNA. As there was no specification regarding this temperature, it has been assumed that temperature range is comprised between -55ºC (218ºK) and 80ºC (353ºK). The code used to make the table is in Appendix 4.

- The table be 3.2 suggests that the noise floor complies with the LNA specification (-88dBm) for temperatures ranging from 215º K and 245º K looking at both bandwidths simultaneously.
- From the table, it can be seen that the noise through the temperature of operation and through the bandwidth is approximately 2.3 dB.

Table 3.2: Noise at lower and upper frequency of the MSP430-VDG-160

T(K)	No1(dBm)	No2(dBm)
215	-88.92	-88.647
225	-88.723	-88.45
235	-88.534	-88.261
245	-88.353	-88.08
255	-88.179	-87.906
265	-88.012	-87.739
275	-87.851	-87.578
285	-87.696	-87.423
295	-87.546	-87.273
305	-87.401	-87.129
315	-87.261	-86.988
325	-87.126	-86.853
335	-86.994	-86.721
345	-86.866	-86.593
355	-86.742	-86.469
365	-86.621	-86.349
375	-86.504	-86.231
385	-86.39	-86.117

2.3dB

1.4 µW

1.6µW

1.9 µW

2.2 µW

- At 215ºK, the LNA's noise has been found to be equal to 1.4µW
- By keeping the LNA's temperature below 255^{0}K, thermal noise becomes 1.6µW.
- At 355ºK, the thermal noise will be 2.2µW

3.2.3 Observations

At the lower limit of the temperature of operation, the noise power is 1.4µW. At the upper of the temperature of operation, the noise power is of 2.2µW (Table 3.2). Therefore, by keeping the temperature at 218^{0}K, thermal noise will be kept to 1.4µW, thus rescuing about 0.9µW. A cooling system has to be designed to maintain the LNA at temperatures from -18ºC to as low as -55^{0}C and the truck to the room temperature comprised between 22^0 C and 25^{0}C for the comfort of the space mission operators.

3.2.4 The system requirements and summary

The preliminary design was devised following critical values stated in the observations above. This section covers the system requirements and the overall system layout.

The system requirements towards the system design were made after the quantitative study.

- The design is meant to maintain the temperature inside the truck to the room temperature (295ºK) as the ground operators will need to be in a comfortable environment. In case the temperature exceeds the room temperature, the cooling system must be started off.
- The maximum allowable thermal noise corresponding to the room temperature was set to -88dBm. This is another case, where the cooling system should be started off.
- The system has to ensure that the LNA is safe even for high power signals (Figure 3.9). The limit was set to 24dB. This value was fixed referring to the maximum input power and to the 1 dB compression (Table 3.1). The controlled system will ensure that no higher value signal than that limit is channeled to the LNA.

The whole system has to be controlled by using a control system. The system will be fitted with a control system so as to receive the analogue quantities namely; the temperature and the downlink signal, and to output the analogue signal to command the cooling system's thermostat and to channel the signal to the LNA (Figure 3.10).

Table 3.3: System requirements

Parameters	Values (max)
LNA temperature (ºK)	255
TruckTemperature (ºK)	298
Input signal (dBm)	24
Noise (dBm)	-88

However, though the overall system layout comprises stages namely; the low energy and the control of the temperature and downlink signal, the research project remains focused on the low energy cooling technology for the particular application of satellite mobile ground station.

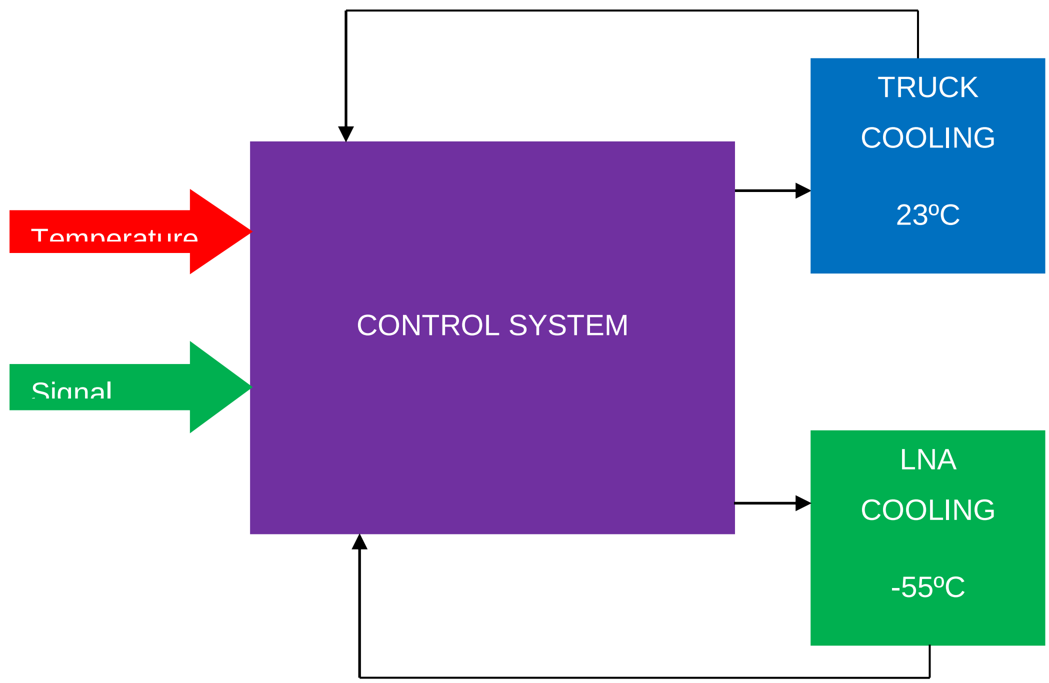


Figure 3.10: Overall system layout

The control system should be a closed loop system (Figure 3.10). It will have two inputs namely; the temperature from the truck and the LNA. Whenever the temperature is found greater than the reference temperatures as seen in the Table 3.3, the control will start the appropriate cooling system and this control will be constantly carried out. Whenever the temperature at either the truck or the LNA is found equal to the reference temperature, the control system will momentarily disable the corresponding cooling system and so forth.

CHAPTER FOUR: SYSTEM DEVELOPMENT

4.1 Introduction

The system development chapter covers the choice of the suitable technology to the mobile satellite ground stations among those reviewed in the literature, the challenges encountered in applying solar based cooling technologies when it comes to the mobile satellite ground station and the possible solution to overcome these challenges.

4.2 Solar based technology classifications

Solar based technologies can be classified with regards to the cooling temperatures, to the coefficient of performance and to the cost involved in their development and implementation.

4.2.1 According to the cooling temperatures

Solar cooling technologies classified into two main categories: electric powered and thermal driven. They have been classified according to the cooling temperatures andcoolingeffects as detailed in Table 4.1(Mittal *et al*., 2008):

Table 4.1 Categorization of refrigeration cycles according to the temperatures

Energy source	Refrigeration cycle	Cooling effect	Temperatures (˚C)
	Desiccant		
	Ejector	Air conditioning	15-20
Solar thermal driven	Rankine		
	Absorption (1)		
	Adsorption		
	Chemical reaction		
		Food and vaccine storage	0-8
	Thermoelectric (2)		
PV driven	Vapor compression		
	Stirling	Freezing	Below zero

Adapted from Mittal *et al*. (2005)

(1): According to the author, the absorption cycle could be suitable for the air conditioning and the food and vaccine storage.

(2): Thermolelectric cooling could be suitable forthe food and vaccine storage as well as the freezing.

4.2.2 According the coefficient of performance (COP)

The table 4.2 shows that solar thermal collectors have a several times larger efficiency as compared to the photovoltaic cells. However, when it comes to the refrigeration cycles, photovoltaic cells offer better COPs.

Table 4.2: Classification according to the efficiency and the COP

Item		**Efficiency/COP**	**Overall COP**
Energy source	Photovoltaics	0.1	
	Solar collectors	0.5	
Electrical driven	Vapor compression	3.0	0.3
	Stirling	1.7	0.17
	Thermoaccoustic	2.0	0.2
	Magnetic	3.0	0.3
	Thermoelectric	0.5	0.05
Thermally driven	Absorption		
	Double effect	1.2	0.6
	Single effect	0.8	0.4
	Adsorption		
	Single effect	0.7	0.35
	Desiccant	0.7	0.35
	Ejector	0.3	0.15

Adapted from Kim and Infante, 2008

4.2.3 According to the cost

The table 4.3 has been proposed by Kim and Infante in 2008. We the author of these thesis have given relied on the study conducted by the mentioned authors, though not up–to-date, because it gives a clear idea of the cost and allows us to establish a comparison between various refrigeration cycle. As regards the prices, the figures are given in Euros.

Table 4.3: Categorization according to the price per 1kW

Refrigeration cycle	Photovoltaics	Collectors + Engine (€)	Chiller	Total (€)
Vapor compression	1,700	2,300	200	4,200
Thermoelecetric	10,000	12,300		22,300
Stirling	2,900	3,800		6,700
Thermoacoustic	2,500	3,300		5,800
Magnetic	1,700	2,300		4,200
Absorption	Solar thermal collector			
Double effect		900	300	1,200
Single effect		600	400	1,000
Adsorption				
Single stage		700	500	1,200
Desiccant		700		700
Ejector		1,700		1,700

Adapted from Kim and Infante, 2008

4.3 Summary

In the selection of the cooling technology, there are two cooling levels involved: the cooling of the amplifier and the cooling of the truck itself.

According to the critical design requirements (Table 4.3) whereby the LNA has to be maintained to the maximum of 255ºK (-18ºC), the PV driven refrigeration systems could be the best for the duty. Also, given the electronic family of the LNA, thermoelectric cooling can be seen to be in a better position as it complies with the electronics cooling. The advantage of thermoelectric device via the Peltier effect of not having moving parts makes it the best technology to cool the LNA. However, thermoelectric device has two setbacks. Looking at the device from the COP point of view, the thermoelectric device has very low coefficients of performances that can be as low as 0.5 (Table 4.1). In reality, this COP value suggests that for the thermoelectric device to produce 500 W, it has to receive 1,000W from the solar cells. This COP is about six times smaller than the vapor compressor's one. From the cost point of view, thermoelectric cooling is too expensive as compared to the other technologies. According to Kim and Infante, 2008, the vapor compression cost was about €4,200 whilst the thermoelectric cooling was €22,300 per 1 kW.

Despite the merits of thermoelectric cooling, the cost and the COP rock it down and preference is given to the vapor compressor system which the cheaper and more efficient of the electric driven models.

It has been said that the receiving equipment will be hosted in a truck along with a probable team of the space mission operators. Therefore, comfort temperatures are to be maintained within the truck for the wellness of the mission operators especially. Solar thermal driven technologies such as the absorption and the adsorption are the best when it comes to the air conditioning systems. The absorption cycle has a COP relatively higher as compared to other solar thermally driven systems (Table 4.2). However, thermally driven COPs are up to four times less than the electric driven systems. But the overall performance is compensated by the high efficient of the solar collectors. In terms of the cost, thermally driven systems are significantly affordable as compared to their electric driven systems.

However, the mobile aspect of the mobile ground station and the structure of these systems do not make these cooling systems the best candidates for MSGS applications. The fact that the refrigerants used in these cooling systems are of liquids can raise instability problems. Both the sorbate and the sorbent are liquid. The moving truck change in velocity or direction can generate storms and waves in the generator and then generates disturbances in the whole cooling system. Furthermore, solar thermally driven refrigeration cycles have many moving parts and large amounts of liquids in the heat storage tanks and cooling tower that are likely to undergo disturbances at any random change in the motion of the truck.

The chosen cooling technology for the satellite mobile ground station applications is the solar electric powered vapor compression system for both the truck and the low noise amplifier. A 2 kW vapor compression was judged sufficient to do achieve the cooling in the context of this project. This power was estimated referring to the cooling appliances commonly used in households. Therefore, the solar system or photovoltaic system will have to provide 2 kW to the vapor compressor. For this to be achieved, a battery system will be placed between the PV system and the vapor compressor due to the non-uniformity of the solar power supply. The layout of the cooling plant is shown in Figure 4.1.In this plant layout, the PV system is the one making problems due to the mobile aspect of ground station under study in this project.

Regarding the power source, the PV system with a pyramid topology was selected among other possible topologies. As for the power required to cool the truck, 1 kW was estimated to be sufficient to meet the cooling of a unit of the SMGS size. In order to determine the rating of the PV system and the one of the vapour compression, the PV efficiency and the COP of the vapour compression system are to be taken in account. It has been seen in the literature review that the PV efficiency is estimated to 10% while the vapour compression COP is of 0.5 (Kim and Infante, 2008). When it comes to the overall efficiency of the whole cooling system, it is can be given by equation 2.1. According to the equation, the overall efficiency of the system is equal to the product of the elements' efficiencies. Therefore, the efficiency of the cooling system will be equal to 5%.

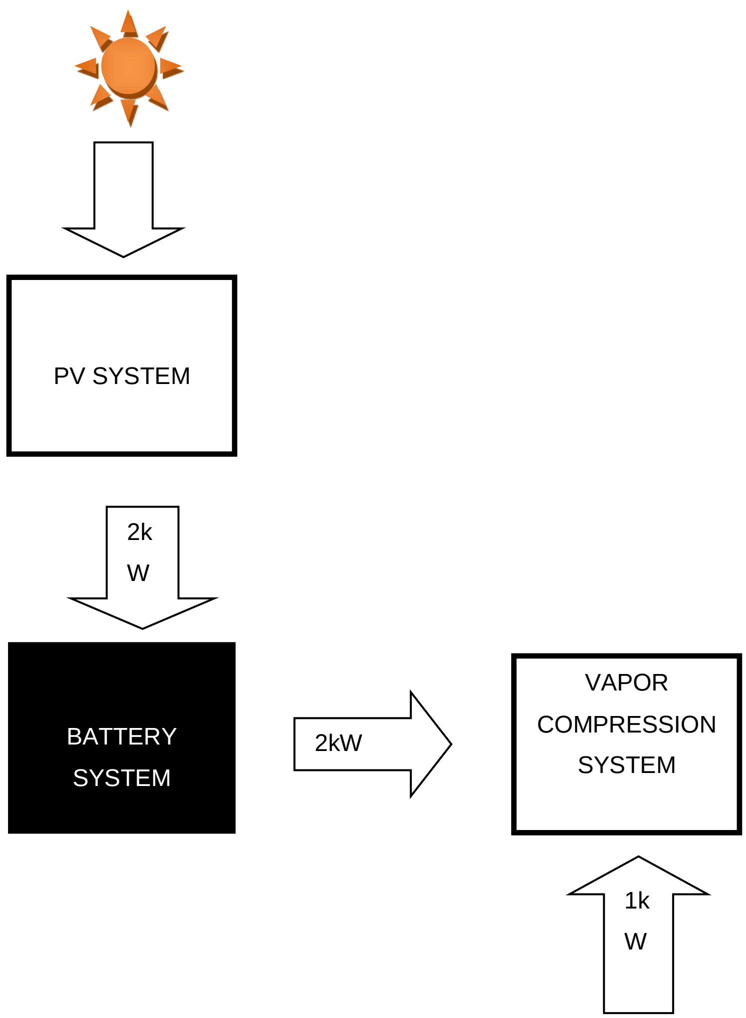


Figure 4.1: Layout of the cooling plant

CHAPTER FIVE: STUDY OF THE PV SYSTEM

5.1 Introduction

Solar energy has been known to the construction sector especially with regards to the power supply in remote areas or in the air conditioning of buildings in hot regions or in the heating of water during the hot summer seasons. In this case, the photovoltaic panels are pointed towards the North if the building is in the Southern hemisphere and to South when the house is in the Northern hemisphere to face the sun. At the equator, the photovoltaic panels are oriented towards the zenith in order to receive the maximum amount of the solar radiation. In this situation, solar panels are given permanent orientation with an appropriate inclination angle so as to optimize the solar radiation reception. The inclination angle is determined based on the latitude the building to be electrically supplied is located. Simulations have shown the variation of solar radiation on the photovoltaic panel with respect to the East to West sun apparent motion. Also, the effect of the variation of the solar radiation on the photovoltaic panel with respect to the variation of the inclination angle between the ground (Earth) and the photovoltaic panel was simulated.

5.2 Simulations of the photovoltaic behaviour versus thermal radiation

Simulations were performed with the help of MATLAB 7.5 software package as follows:

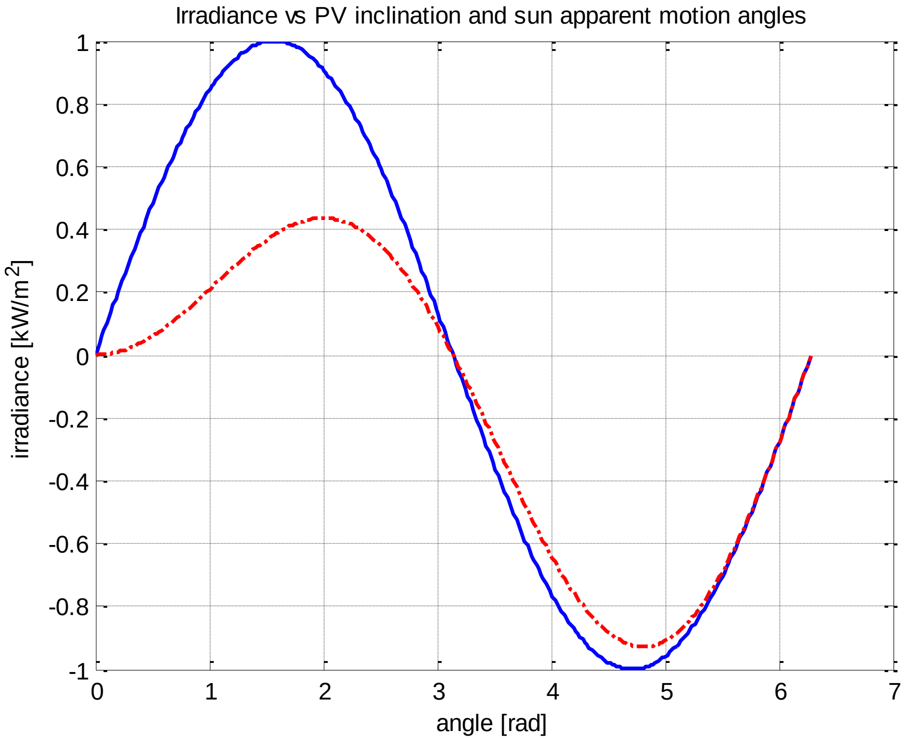


Figure 5.1: Irradiance vs PV inclination and apparent motion angles

The graph simulating the effects of the sun's apparent motion has taken into consideration the fact that the motion has completed a full day. In other words the sun has moved from the sunrise of one day to the sunrise of the following day. In terms of angles, the sun has apparently completed a full cycle equivalent to two pi (360 degrees). Regarding the inclination angle between the photovoltaic panel and the ground, it has been assumed to be the maximum, which means pi (180 degrees).

The effect of the sun's apparent motion on the irradiance (curve in uninterrupted blue in Figure 5.1), in the first half of the cycle (0-π), the irradiance is positive and multiplied by the sine of the corresponding sun's position during its apparent motion. In this positive half of the cycle, the photovoltaic panel is receiving the solar radiation (measured as irradiance) whilst in the second half of the cycle, which is negative, the photovoltaic panel is losing heat energy to the atmosphere.

The effect of the inclination angle on the irradiance received from the sun (red curve of figure 5.1) suggests that that the irradiance received by the solar panel from sun is multiplied by the sine of the inclination angle. The resultant irradiance is less or equal to the one on the blue curve. The only way to maintain the irradiance maximum is to make the sine of the irradiation angle equal to 1. This condition can be satisfied if and only if the solar panel is perpendicular to the solar radiation plane.

However, in reality a rectangular shaped solar panel receives solar radiation only during the day. Therefore, the sun's apparent motion angle starts from 0 radians and ends at 2 pi radians. As for the inclination angle, the solar panel can only be exposed to the sun for an angle varying from 0 radians to pi/2 radians. This realistic assumption yields the following graph (Figure 5.2). This graph suggests that at the sunset (0radians), the irradiance is minimum and close to zero. This point corresponds to the sine of zero which is equal to zero. The same situation is found at the sunset when the angle is equal to pi. The irradiance will be maximum at noon when the solar radiation is perpendicular to the solar panel's plane. This is the point corresponding to pi/2 and the sine is equal to 1. The inclination angle (red curve of Figure 5.2) suggests the same effect as in the previous case. The code for plotting the graphs is in Appendix 5.

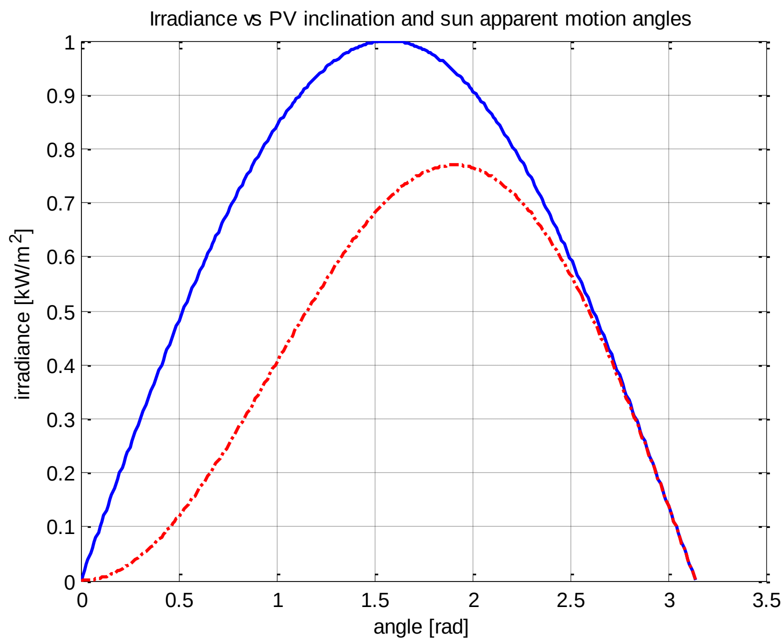


Figure 5.2: Realistic simulation of the effects of the angles

5.3 Challenges in powering the SMGS cooling system via solar power

It has been seen in the introduction that the solar radiation received by a rectangular shaped solar panel depends on the inclination angle and the apparent motion of the sun. The inclination angle of the solar panel can be adjusted whereas the sun's apparent motion is a rigid parameter. On top of these two angles, there is also another angle linked to the mobile aspect of the SMGS. This angle will be taking direction depending on the direction the truck is going. The truck may be going North, South, East or West and other intermediate directions like North East, North West, South East and South West. These angles are overviewed as follows:

5.3.1 The photovoltaic inclination and PV system angle-exposure to the sun

The photovoltaic inclination angle is the angle between the tangent to the earth's surface and the photovoltaic panel's normal. This angle must be set such that the sun's apparent motion is perpendicular to the photovoltaic panel plan. This angle depends on the geographical position especially the latitude on which the solar panel is located and on the season as well. Table 5.1 shows the inclination angles for South Africa. For instance at the equator line, the solar panel is set parallel to the tangent of the earth surface. Therefore, the inclination angle is equal to zero. This way, the solar panel is exposure to the sun is optimum (Figure 5.3)

Table 5.1: Optimum inclination angle in South Africa

	Longitude																		
Coordinate	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
Latitude																			
23												45,2	51	53,1	53	49,5	56		
24												42,3	50,6	45,2	46	49,2	50	55	
25					33	32,8	32,1	37	41,8	41	42	44,4	49,9	47,1	49,1	53	53		
26					34,3	38,7	35	41	38,5	42,8	43	45,1	48	50	46,9	53	49,7		
27				33,6	35,9	38,6	40	41,1	44	45	47	49	53	51,8	52,3	57,6	55		
28	26,3	28	28,2	28,6	32	32	41	36,7	38	45	46	44	42,2	50	49	52,8	57	55,3	
29	28,9	29	27,4	29,7	37,8	37	43,1	41	40	42	41,4	43	47	48,4	44,5	51	53	56	
30		26,7	33,9	31,6	34,2	35,4	35,8	37,0	41,2	41,9	44	50,4	47,7	50,3	45,5	55,1	56,5		
31		29,7	30,7	36,4	31,5	36,7	34,3	36,1	38,3	42,2	43,9	43,6	49	47,3	50,1				
32			35,7	34	30,8	34	40,9	39,1	40,7	42,1	43,2	45,2	45,7	48	50,1				
33			40,1	37,7	38,8	41	47,1	44	47	48,6									
34			38,2	38,9	42,8	40,3	41,8	41	45,1	44,9	48,2								
35				38,2					46,3										

Adapted from Matshage and Sebitosi(2011).

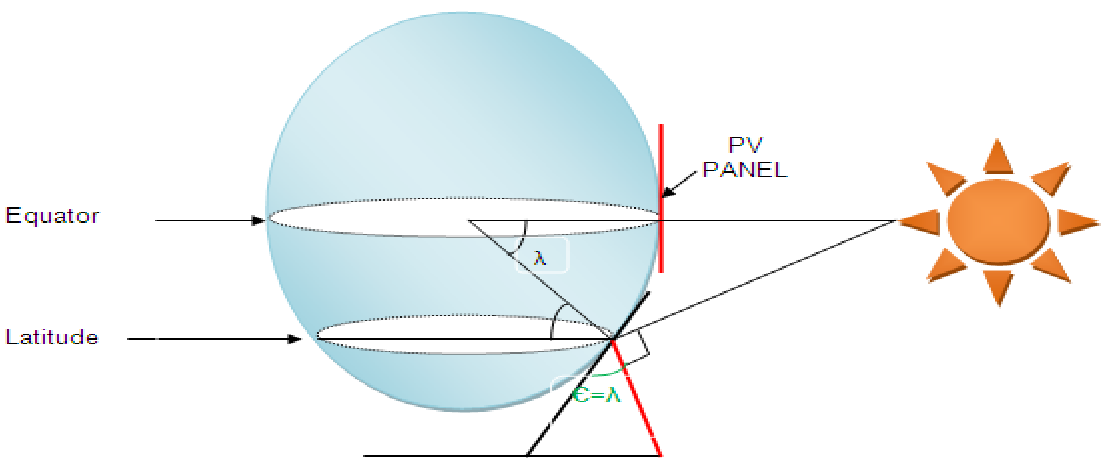


Figure 5.3: Inclination angle computation

Where λ is the latitude and є is the inclination angle.

In the case of FSATI satellite mobile ground station, the inclination angle of the PV panels on top of truck has to be determined referring to the latitude and longitude on which the Cape Peninsula University of Technology Bellville campus is. The GPS coordinates of the CPUT Bellville campus are given as follows: 33º55’56’’ S; 18º38’25’’ E. For the inclination angle of the PV the only data needed is 40.1^0 according to Matshage andSebitosi (2010).

5.3.2 The effects of the mobility of the SMGS on the solar irradiation

The effects of the mobility of the SMGS on the performance of the solar panel have been touched in the previous section. In this section, a detailed study has been provided and supported with relevant schematics and simulations.

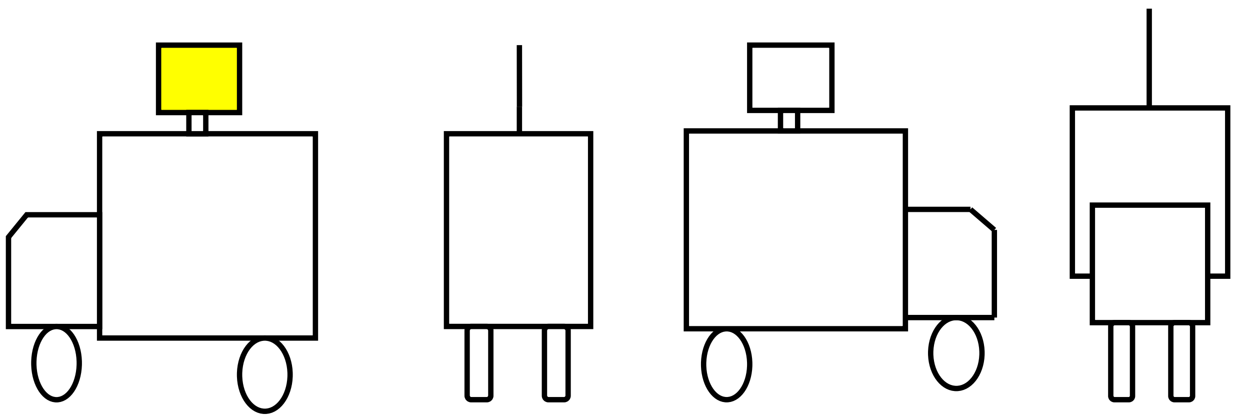


Figure 5.4: Effects of the rotation of the truck on the PV exposure

The figure 5.4 gives the main possible directions the truck can take to yield a solar panel area full solar exposure (panel painted in yellow) and directions where the solar panel exposure is quasi not impossible. In terms of cycles, in the whole cycle, the solar panel will only be illuminated for a quarter of the cycle (0-π/2). The solar panel is assumed to be one side active the other side consists of the substrate and other supporting material and this will obviously affect the performance of the solar panel.

The performance of the solar panel was simulated with regards to the direction change of the truck (Figure 5.4). The inclination angle was assumed to be perpendicular to the sun's apparentmotion plane. In this simulation, the sun was assumed static with respect to the truck's change of direction. The inclination angle was assumed to be constant as well. If the solar panel is statically fixed on the truck, it will receive solar radiation for a half cycles only. The remaining half, the solar panel will be in the shade. During this time, the cooling system will be without any power.

5.4 Study of photovoltaic topologies to meet the challenges

To mitigate the problem of non-uniformity and sustainability of power supply to the SMGS cooling system, a proper topology of solar panels has to be put in place to ensure that the trucks rotational movement does not affect the cooling system operation. The aim is to have the large area of the solar panels possible exposed to the sun in spite of the rotation angle of the vehicle containing the mobile ground station. In addition, the PV topologies have to be efficient in terms of area and power delivery. Among suggested topologies are single sided solar panel, double sided solar panel and pyramid respectively. The lateral surface of a pyramid should make an angle with base equal to the inclination angle. Proposed PV topologies are shown in Figures 5.7 and 4.8. Figure 4.8 shows them as mounted on the truck for the satellite mobile ground station. Their performances were simulated and the results were given in the next section.

5.4.1 Model for a PV system

In order to define the model of the PV system, it is important to remember the PV system in the context of this project. A PV system or a PV topology can be defined as any system of one or more solar panels that are used to supply the power to the cooling system.

The model was defined for one reference solar panel of the PV system and for the other solar panels; the model was a deduction of the reference solar panel. The model for the reference solar panel in terms of the power delivery referred first to the change of the irradiance due to the rotation of the solar panel. The model was established starting at the point where the reference solar radiation reaches the solar panel with an incident angle of 0 radians. In this case, the irradiance is equal to zero. With the increase of the incident angle, the irradiance will increase and will reach its maximum when the incident angle is equal to π/2 radians. Afterwards, the irradiance will decrease again to reach zero value at the incident angle equal to π. This model was simulated with a Simulink model in Figure 5.5 and Appendix 6.Its output is shown in Figure 5.6.

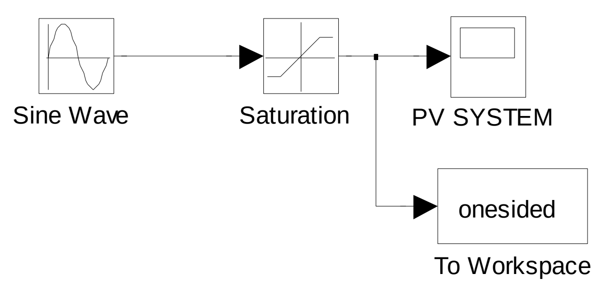


Figure 5.5: Model of a solar panel in rotation

As the power performance is dependent on the criteria namely the PV system exposure to the sun and the efficiency, the study was made based on these two criteria. This study was achieved by using simulations performed in MATLAB. The model for simulation had to be defined for these simulations to be completed.

5.4.2 According to the exposure to the sun

5.4.2.1 A single sided photovoltaic panel topology

The single sided topology uses one solar panel to provide the power to the cooling system. It will only be able to provide the power for a half cycle in case the vehicle beholding the ground station performs a complete rotation (Figure 5.6)

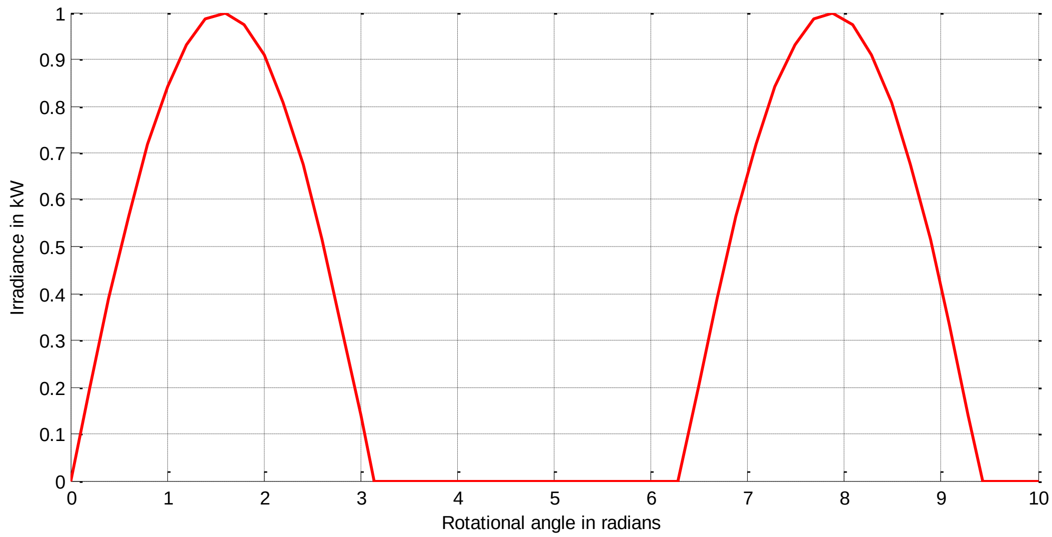


Figure 5.6: Simulation of the solar irradiation from a single sided photovoltaic panel

5.4.2.2 Double side photovoltaic system topology

Solar panels with front and back side are active could offer a better topology to supply the power to the cooling system for the satellite mobile ground station. The simulation of the PV system is shown in Figure 5.7.The Simulink model is given in Appendix 7.

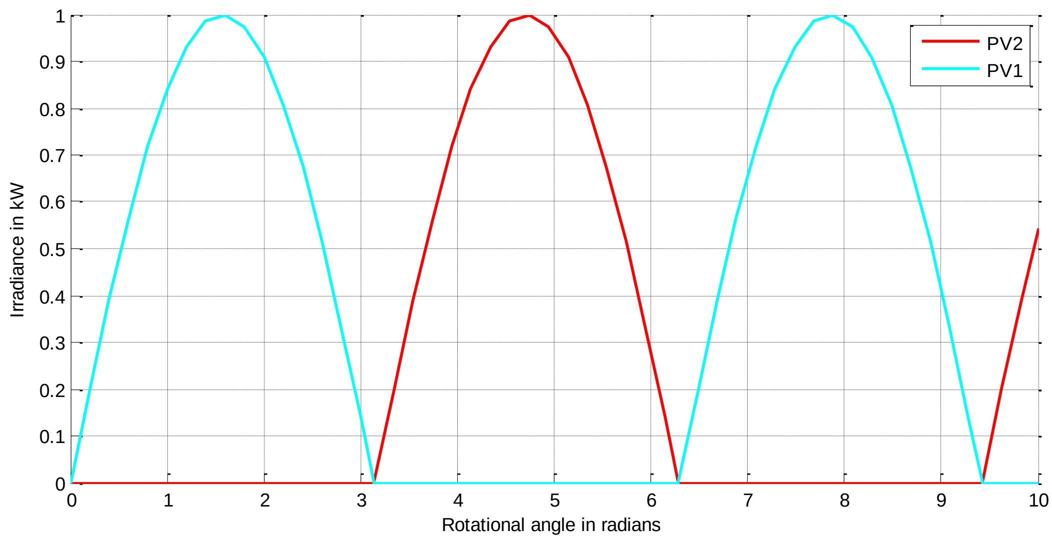


Figure 5.7: Simulation of a double sided topology

The photovoltaic will be working in a way that each active side will individually work for a period of pi to be relayed by the second active side. It is necessary to remember that the rotation of the truck corresponding to the change of direction is not uniform. In other words, the truck can dwell in a position whereby the double sided photovoltaic system is not oriented in the prescribed angles and thus unable to deliver the required power to run the cooling system. As a consequence, the batteries will be affected and the objective of the cooling process will not be properly achieved.

5.4.2.3 Three sided pyramid topology

A three sided pyramid can be seen as a PV system having a shape of pyramid having three active sides. The graph in Figure 5.8 shows that the PV system will consistently provide 90% of the solar panel nominal power. The Simulink model is given in Appendix 8.

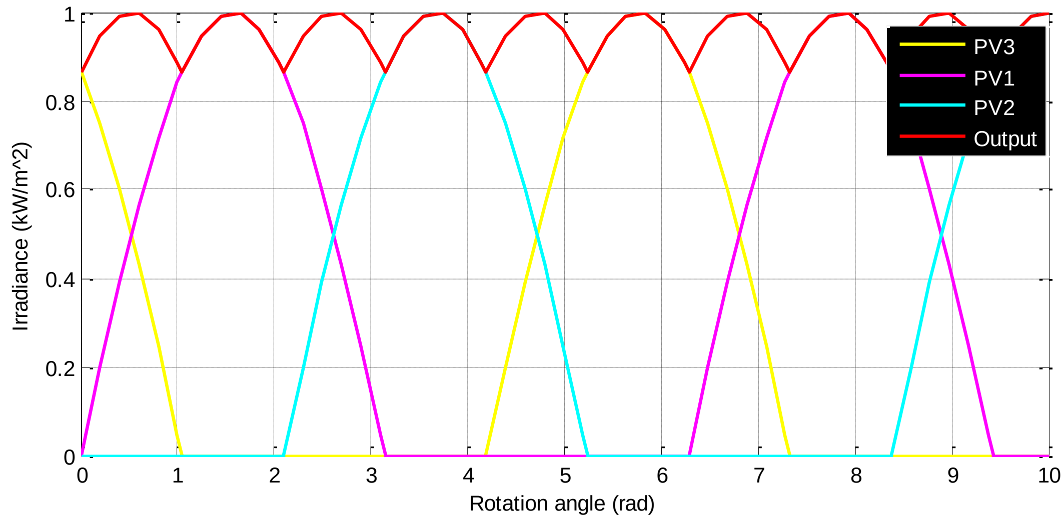


Figure 5.8: Simulation of a three sided pyramid in rotation

5.4.2.4 Four sided photovoltaic panel topologies

A four sided photovoltaic can be viewed as a topology whereby the photovoltaic system will have four active sides. There can be a variety of four sided photovoltaic topologies of which the pyramid with the trapezoid sides and pyramid with triangular sides.The simulink model is given in Appendix 9.

The trapezoid topology is one of the possible ways of having at least one solar panel exposed to the beam of solar irradiation when mounted on the mobile satellite ground station. For this topology to supply power to the cooling system, the angles between the basis and the side areas must be equal to the required inclination angle so as to have the solar radiation plane perpendicular to the solar panels.

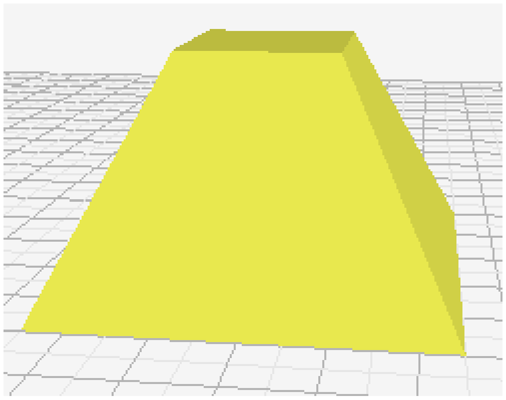
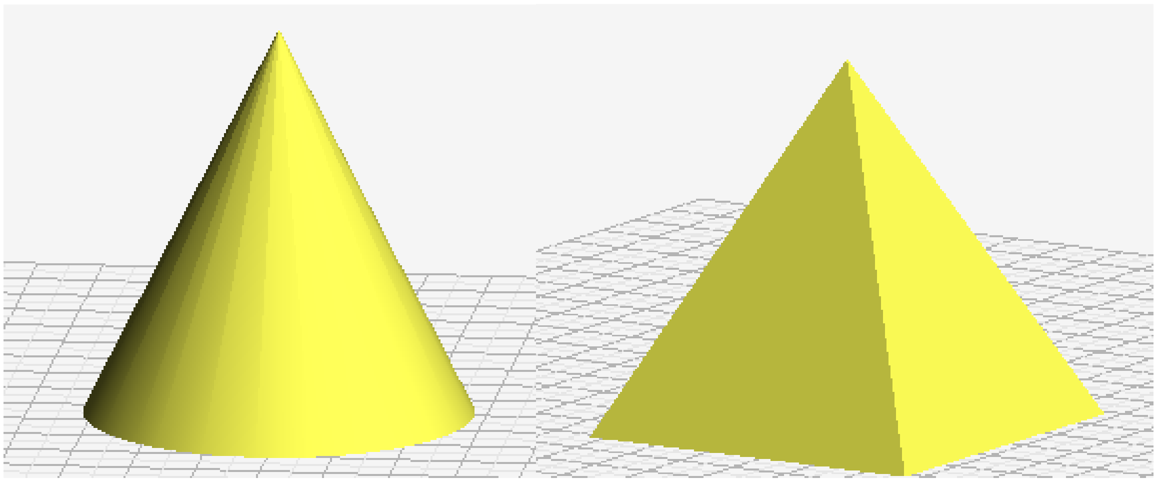


Figure 5.9: Trapezoid topology

The pyramid topology is another means that can be used to supply power to the cooling systems. There are two main types namely a pyramid with a circular basis and a pyramid with a square basis as shown in Figures 5.10. Once again these topologies will allow the truck have at least an area of solar panel exposed in case the truck performs a rotational movement (Figure 5.11).



(a) (b)

Figure 5.10: Pyramid topology

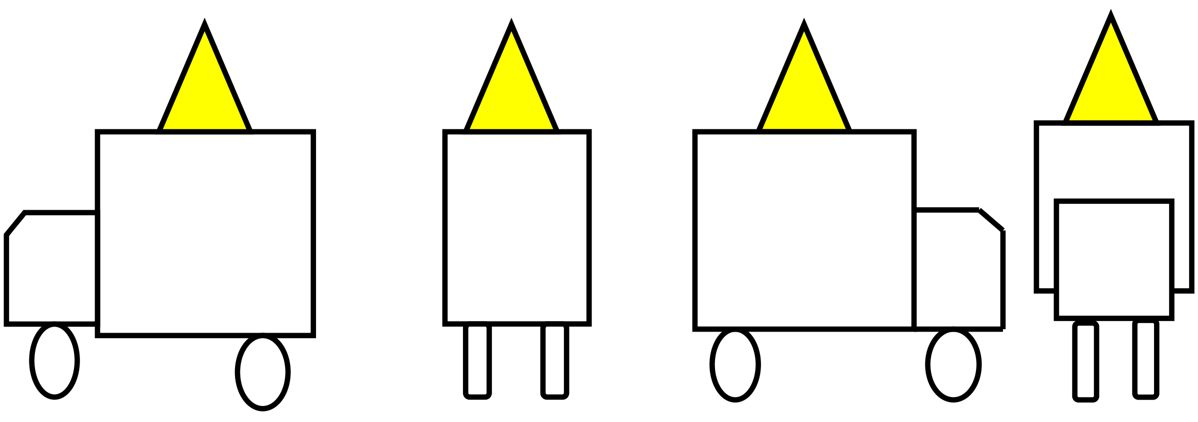


Figure 5.11:Illustration of a four sided topology mounted on a truck in various directions

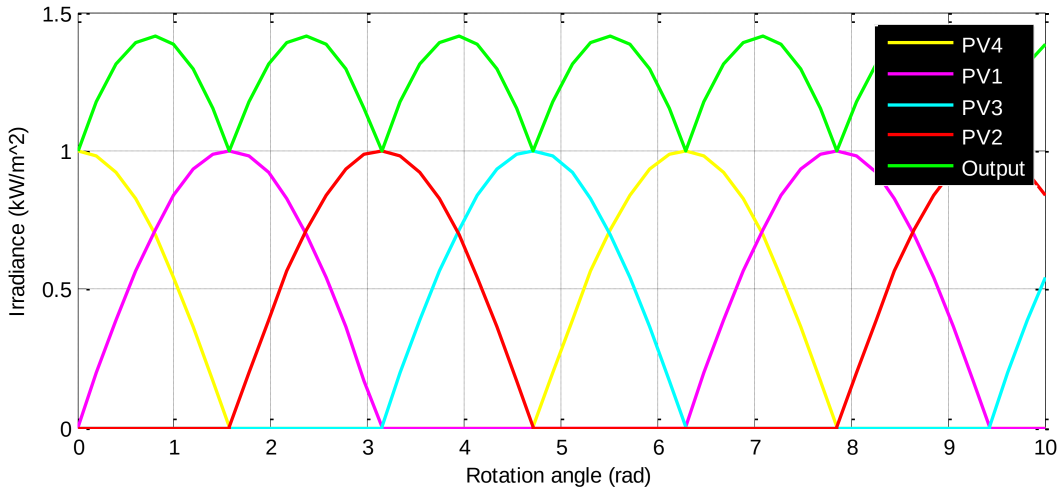


Figure 5.12: Pattern of the irradiance for a pyramid with a square base

The pyramid topology with a square base shows that the solar photovoltaic system will be able to supply power to the cooling system constantly at 100 % of the nominal power (Figure 5.12). This topology is a good candidate to meet the challenge of no uniformity in supplying the power.The idea behind the simuations is that the photovoltaic system will have two adjacent active sides exposed to the sun at a time. When the first side rotates up to angle of 90 degrees, one of the adjacent sides starts seeing the sun thus converting thermal energy into the electric power and so forth.The simulink model is given in Appendix 10.

5.4.2.5 Five sided PV topologies

The five sided PV topology can be developed with the help of pyramids as well. Figure 5.13 shows that the topology will be able to consistently supply 160 % of the nominal power to the cooling system. This topology offers an improvement to the previous topologies. The simulink model is provided in Appendix 11.

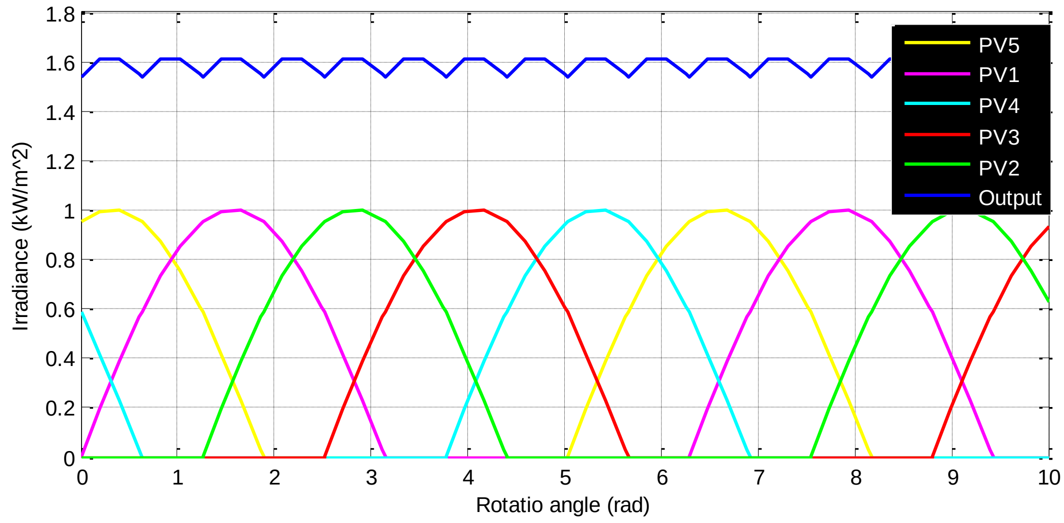


Figure 5.13: Five sided pyramid

5.4.2.6 Pyramid with a hexagonal base topology

The pyramid with a hexagonal base is another topology that can ensure the cooling system is supplied at any instant. In this type of topology, there will always be two or more active sides exposed to the sun (Figure 5.14). The effect on the irradiance is much improved when compared to the previous topologies and approximately 190 % of one active side's nominal power will be certainly delivered to the cooling system. The Simulink model is given in Appendix 12.

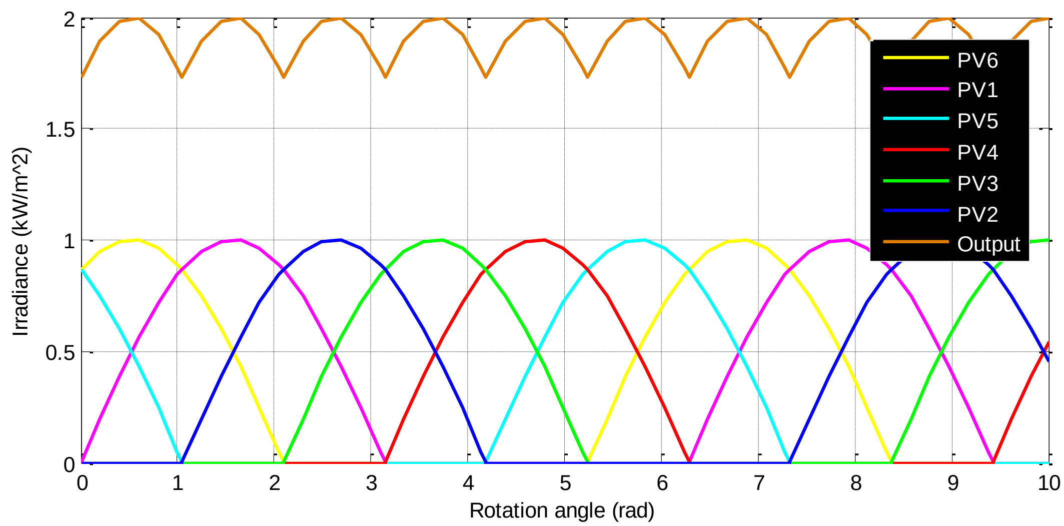


Figure 5.14: Six sided pyramid

5.4.2.7 Pyramid with an octogonal base toplogy

The pyramid with an octogonal base suits the supply of a cooling system installed in a moving truck as well. Again, this topology offers a better perfomance and provides 250 % of one active side's nominal power (Figure 5.15). The simulink model can be seen in Appendix 13.

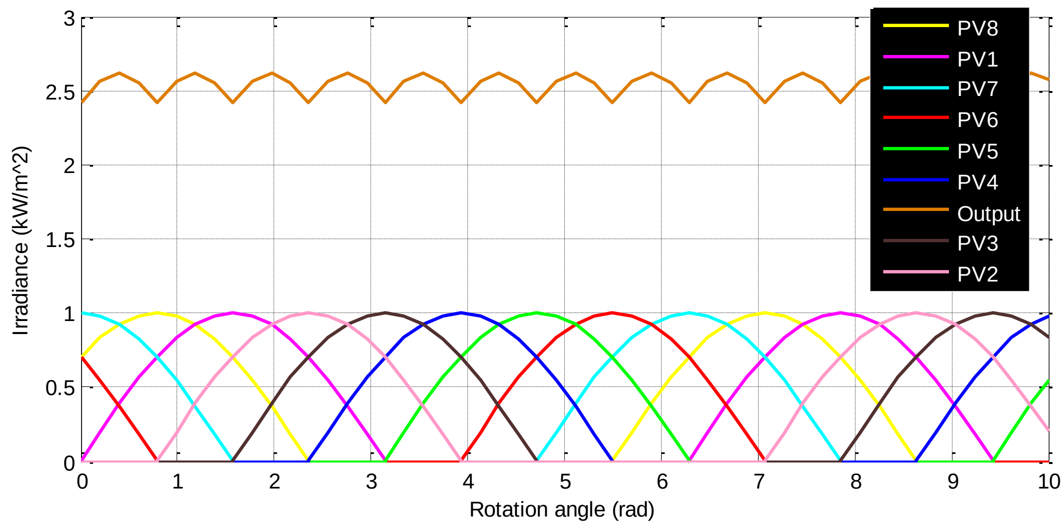


Figure 5.15: Eight sided pyramid

5.5 Summary

Among the photovoltaic topologies studied, namely the single side, the double sided, the three sided pyramid, the four sided pyramid, the five sided pyramid, the six sided pyramid and the eight sided pyramid topologies, we can conclude that the more the active sides of the PV system, the more thermal energy converted into electrical power for the cooling system (Table 5.1). Starting from the three sided pyramid onward, these topologies can guarantee the supply of the irradiance at 50% of the solar panel's nominal power. However, it is important to know which of the topologies is efficient for the sake of the energy and cost savings.

Table 5.1: Performance of the PV topologies

Topology	Output(kW)	Observation
One sided	-	Disqualified
Two sided	-	Disqualified
Three sided	0.9	Fifth
Four sided	1.0	Fourth
Five sided	1.6	Third
Six sided	1.9	Second
Eight sided	2.5	First

CHAPTER SIX: DISCUSSION AND ANALYSIS ON SIMULATION RESULTS

6.1 Introduction

Chapter six of this thesis consists of the analysis of the simulation results obtained from various PV system topologies studied in the previous chapter. One sided, two sided three sided, four sided, five sided six sided and eight sided PV topologies were studied and it has been seen that the larger the number of active sides, the better was the performance of a PV system. However, the larger the number of sides, the more complex and costly the PV system is. Therefore, a factor of comparison is needed to determine which topology is the most efficient and cost effective. By the most efficient, one should understand the PV topology that would require the minimum area of solar panels and perform well in terms of providing the power to the cooling system.

In order to determine which PV topology is more efficient than others, a comparison has to be made between them. A comparison was made by taking all the PV topologies in the same conditions. In this regard, the topologies had to be compared with respect to a reference value. All the PV topologies were assumed made from a main solar panel of 1 m^2 area and of 1 kW/m^2 irradiance. In this case, all the sides of a PV topology share the area of 1m^2. Simulations were performed in Figures (6.1-6.5). The simulations show what would be the output of a topology made from one plain solar panel of which the nominal power is 1 kW. The most efficient topology would be the one with the highest output.

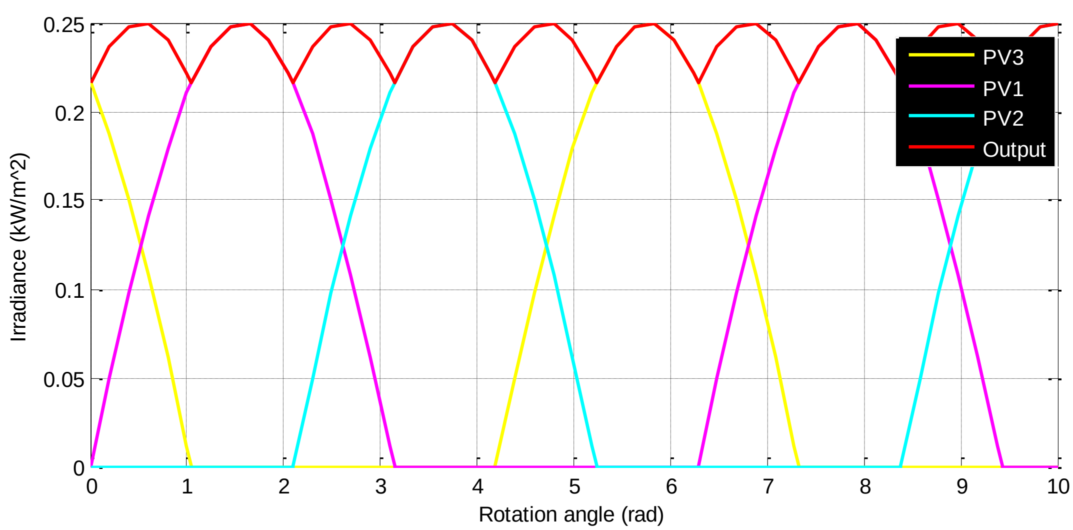


Figure 6.1: Three sided topology in comparison

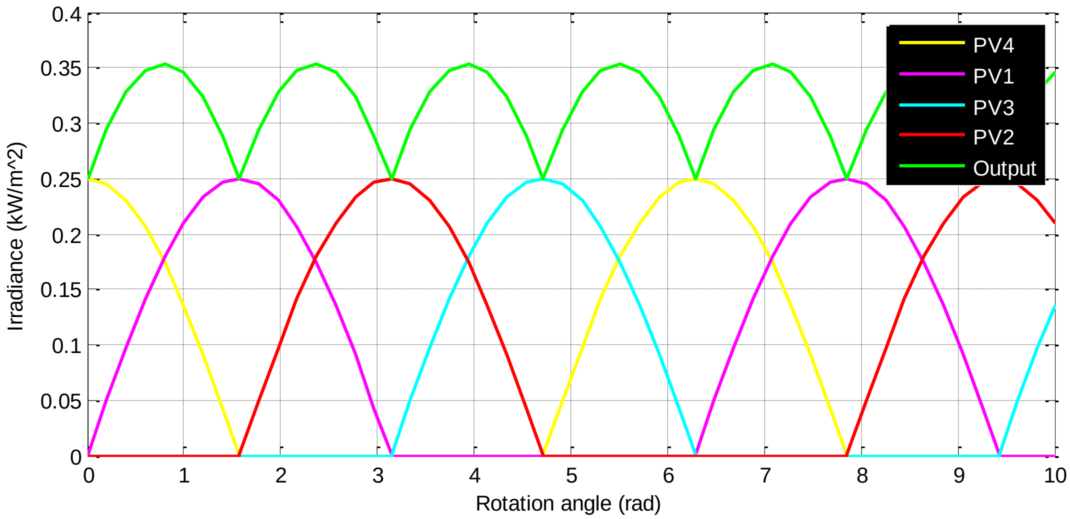


Figure 6.2: Four sided topology in comparison

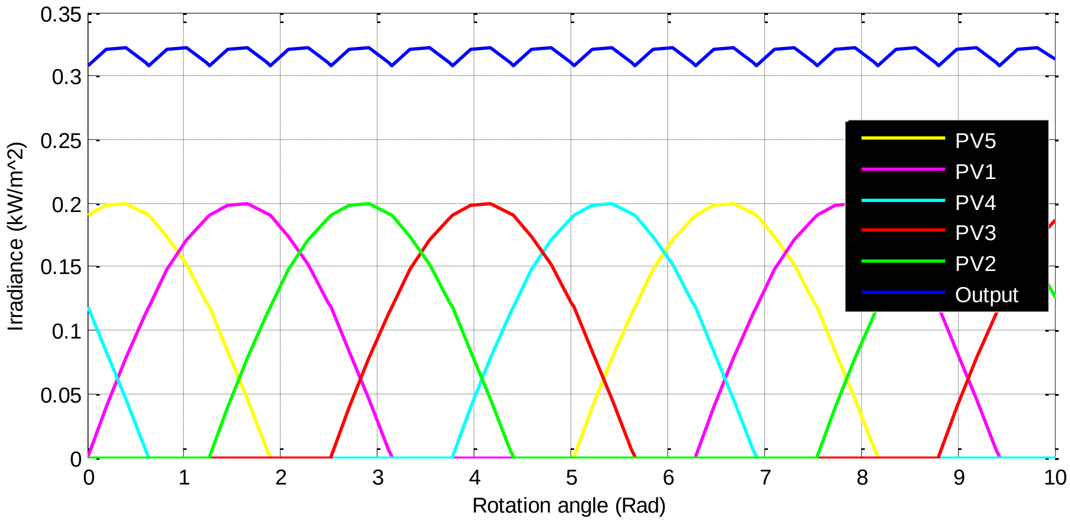


Figure 6.3: Five sided topology in comparison

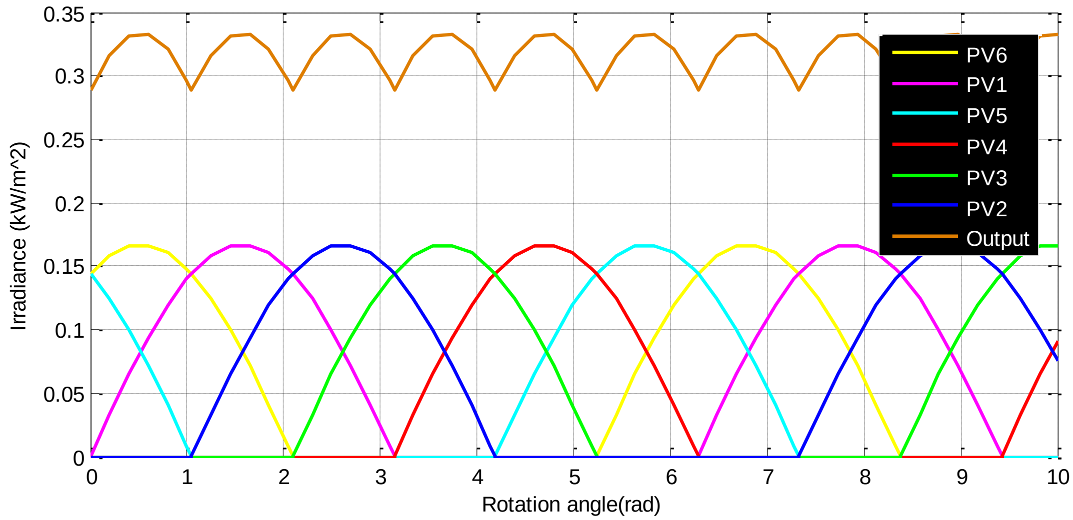


Figure 6.4: Six sided topology in comparison

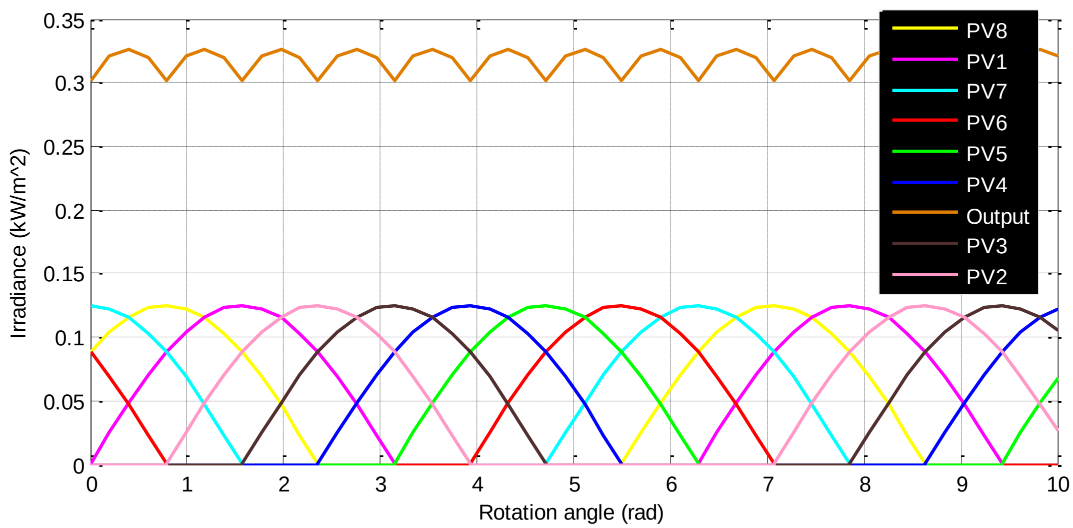


Figure 6.5: Eight sided topology in comparison

The simulations of all the topologies show that all the PV systems will be certainly delivering 31 % of the solar panel's maximum power. Thus, the three sided topology has proven to be the most efficient (Table 6.1) in terms of power and cost. In terms of power because it shows the ability of providing the same power as its protagonists namely the four, five, six and eight sided topologies. In terms of cost, the three sided topology is effective because of the less number of solar panels as compared to other topologies.

Table 6.1: The comparison table

Topology	Output(kW)	Observation
One sided	-	Disqualified
Two sided	-	Disqualified
Three sided		Second best
Four sided	0.31	Best
Five sided	0.31	Third
Six sided	0.31	Fourth
Eight sided	0.31	Last

As a conclusion, all the PV topologies have the same performance. If all the PV topologies in study made from 1 kW standard solar panel are giving the same output power equivalent to 31 % of the standard solar panel.

However, these topologies with a fixed inclination may have drawbacks with regards to the mobility of the ground station. In fact, the sun apparent motion plane will not be perpendicular to the active side's plane all the time for the PV system's active sides to receive maximum radiation. Therefore, it is important to study the effects of the fixed inclination of the PV topology taking into account that the ground station may be operating all over South Africa. From this study, an optimum inclination angle will be determined for the PV topology.

6.2 Optimum inclination angle

The recommended topology (three sided) in the previous section has to be designed to perform well in South Africa and have fixed inclination angles. In addition, the roads are not as flat as one could imagine. The roads have slopes even little they could add a degree or more to the inclination angle of the photovoltaic system. Supposing that the mobile ground station has to operate from the two extreme latitudes of South Africa, the inclination angle will have to undergo a change of approximately 30^0 from the North to the South (Matshoge and Sebitosi, 2011). According to these authors, the least inclination angle is 26^0 and the highest is 56^0 in South Africa. A degree change corresponds to 112 km change in space (Appendix 14). In other words, a spatial change of 112 km would be followed by the adjustment of 1 degree on the inclination angle.

6.2.1 Simulations

The simulations on the performance of the PV system with regards to the change in the inclination angle over South Africa wereperformed in two ways. Firstly, the PV system inclination angle was changing between extreme inclination angles i.e. from 26º to 56^0 (Figure 6.6), thus undergoing a change of $30^{0.}$ Secondly, the PV system inclination angle was set to 41^0 which is the midpoint between the extreme inclination angles observed in South Africa (i.e. the change in the inclination angle can only be 15^0 maximum (Figure 6.7).

In the case of the PV system inclination angle fixed to 26^0, simulation results show that for a four sided pyramid, nominal power set to 1 kW drops to 0.86 kW whereas the consistent power supply to the system drops from 0.7 kW power to 0.6 kW approximately.

In the case where the PV inclination angle is at 41^0, the nominal power drops from 1 kW to 0.96 kW, whereas the consistent power supply of the solar panel undergoes a change 0f 0.02 kW only dropping from 0.7 kW to 0.68 kW.

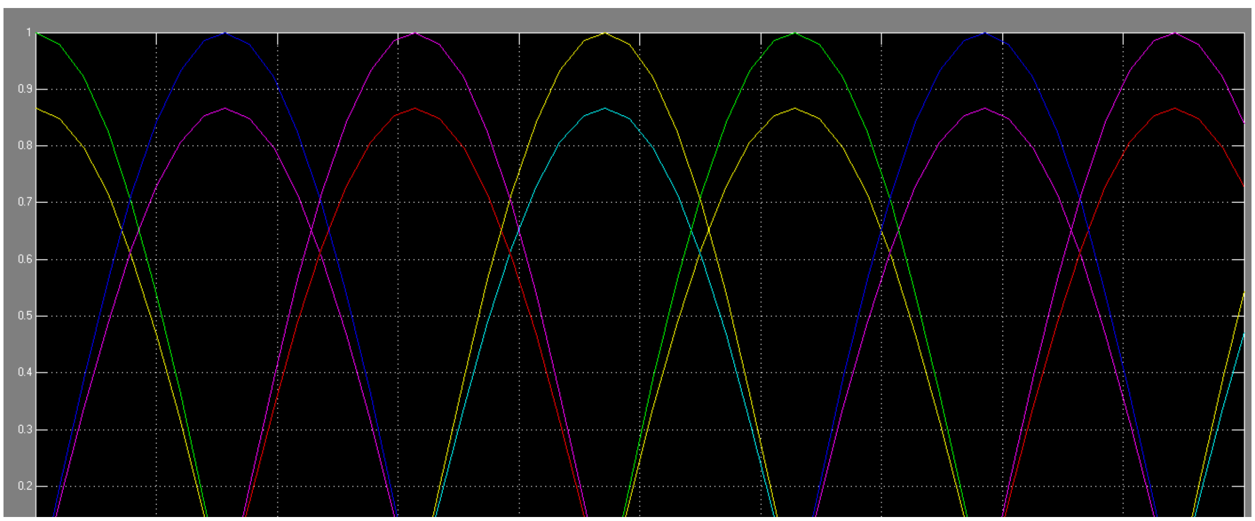


Figure 6.6: Change in output with the inclination angle at extreme values

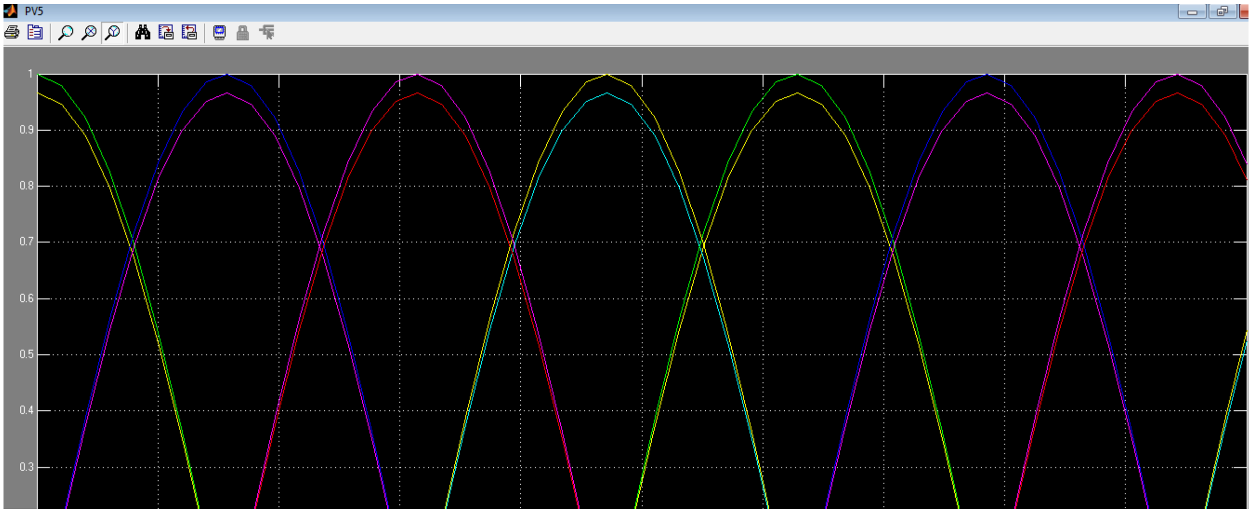


Figure 6.7: Change in output with an optimum inclination angle

6.3 Summary

In a conclusion, a three sided pyramid topology was found to be the best among all the studied topologies for its efficiency, for its simplicity in design and for its cost effectiveness. In addition, 41º has been found out to be the optimum inclination angle for the PV system in the context of supplying the power to the cooling system nationwide. The next point is the development of the cooling plant.

6.4 PV system design and connection

The PV system that was selected to power the cooling system is a four sided pyramid with 41^0 inclination angles (Figure 6.8). Each side of the PV system is meant to be able to provide 2.2 kW, the power required for the cooling system. Each PV system will be independently connected to the battery system. A minimum of one side and a minimum of two will be exposed to the sun at a time.

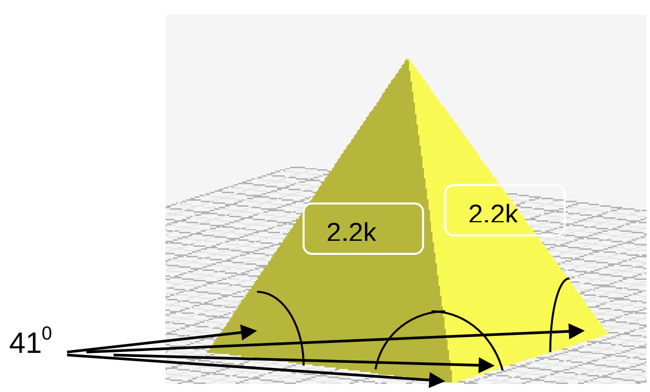


Figure 6.8: Design of the PV system

6.5 Design of the cooling plant

The finality of this project has been the design of a cooling plant. The specifications of the plant were fixed at 2 kW (Figure 4.1). As it can be seen, the cooling plant comprises three main parts namely the PV system, the battery system and the vapour compression cooling system. The cooling operation is such that the PV system converts thermal power acquired in the form of solar radiation and converts it into electrical power to charge the bank of batteries. In turn, the bank of batteries provides the accurate power to the vapour DC vapour compression system. Each part of the cooling plant is going to be seen individually and its detailed specifications are going to be determined.

6.5.1 PV system and battery system

The PV system is the part that is meant to provide the electric power to charge the batteries. It has to ensure that they are meeting the battery charge requirements. The PV system was designed in a four sided pyramid topology as seen previously. For the PV system to be able to certainly supply 2 kW to the vapor compressor, 2.2 kW nominal power approximately is required from each individual solar panel of the PV system. In fact, it has been seen that the three sided topology is able of consistently supplying 90% of the nominal power and therefore, 2.2 kW nominal power will be sufficient to provide 2 kW to the battery system. This power should be evaluated in terms of voltage and current in order to suit the battery's specifications. In other words, the voltage and the current of each solar panel of the PV system should be able to provide the required voltage and current to the battery system. In terms of voltage, the battery system can be designed in the multiples of 12 V as to yield 24 V, 48 V and so forth, depending upon the specifications of the vapour compression machine. In terms of the current, the PV system must provide the current that corresponds to the batteries' specifications when it comes to the energy (Ampere-hours). For the 2 kW vapour compressor requiring 48 V, the battery bank must provide the same voltage and the current of 41.6 A. This current is determined by virtue of the formula by which the power (W) is the product of the voltage (V) and the current (A). Therefore, at the maximum power point (MPP), each side of the PV system would have 48 V and 41.6 A. Regarding the battery system, the energy will be 48V and 41.6 Ah.

6.6 Summary

The design of the cooling plant is detailed in Table 6.2 where specifications are provided. Voltages and currents have been provided for the main components namely the PV system, the battery system and the vapor compressor.

Table 6.2: Cooling system specifications

Item	Voltage (V)	Current (A)	Power (kW)
PV system	48	46	2.2
Battery system	48	41.6	2
Vapor compressor	48	41.6	2

CHAPTER SEVEN: CONCLUSIONS AND RECOMMENDATIONS

As a conclusion for this research project, the design of a clean, human and environment friendly was devised for a prospective mobile ground station in order to reduce thermal noise and keep comfort onboard of the moveable ground station for welfare of the mission operators. Only solar powered cooling units were found to comply with the research question and the objective of this research project.

Among the pool of the solar powered systems, the solar electric vapour compressor was chosen over the rest for its stability and availability at a reasonable price. The cost effective adsorption systems were let down by their use of liquid refrigerants. The latter may be the source of instability in the cooling system especially when the cooling unit changes the speed or when they undergo turbulence due to the change of velocity of the carrier vehicle. Thermoelectric cooling systems were discarded due to the exorbitant cost even though they were found to be the perfect fit for the LNA and electronics cooling. For these reasons, a 2 kW solar electric powered vapor compression unit was chosen to provide the temperatures as low as -55^0 C for the LNA and to keep the temperature inside the truck to at 23^0 C. The system requirements were provided after a quantitative study of the thermal noise.

Regarding the power supply to the cooling unit, various topologies of PV systems were studied. A three sided pyramid topology stood out of the three sided, five sided, six sided and eight sided topologies based on its efficiency and its reasonable cost. Due to the non-uniformity of the solar cells in supplying the power, the battery system was suggested to directly provide the DC power to the vapor compression unit. The ratings power rating of the PV system was estimated at 2.2 kW for each side as to deliver 2 kW to the battery system. Te battery system rating was 48 V and 41.6 Ah as to provide the 2 kW power to the vapour compression unit. The optimum inclination angle for the PV system was found to be 41^0. The overall model of the PV system was provided in this project as it was the only one that was causing problems. For the battery system and the vapour compression system could be acquired from the shelf.

The work presented in this thesis is not limited to the domain of cooling only; it can serve to other purposes as well. This work can help in providing power in any moveable unit. It can also be referred to when it comes to the design of power for spacecrafts. In the domain of building lighting, this work can help improve the output of the PV system as it can somehow help track the sun apparent motion.

Finally, this work has met the objectives and the research questions for this project.

However, this work may be improved in the future for better performances. The current PV system design is such that the power delivered to the batteries is not uniform, and at some rotation angles, the batteries receive the power from two solar panels. This may cause over current to some extent and this should be mitigated by devising an electronic system as to have the solar panels switching sequenceas shown in Figure 7.1.

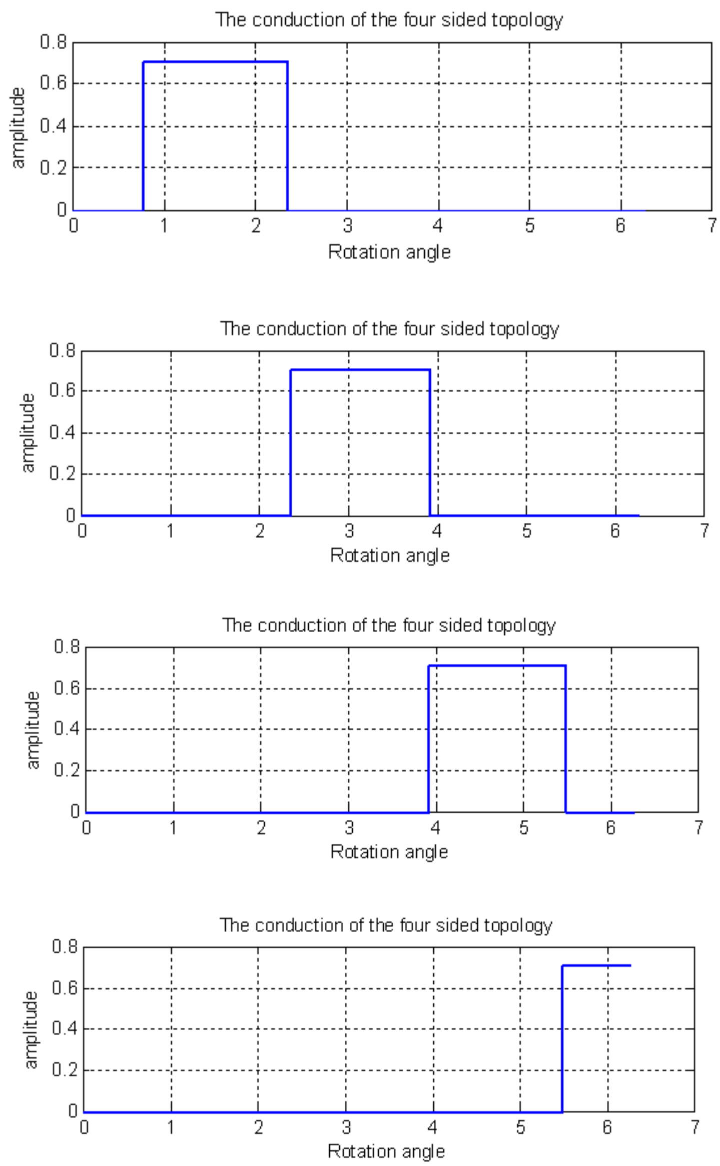


Figure 7.1: The switching sequence of the PV system

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APPENDICES

Appendix 1: Formula to illustrate the gain of the LNA

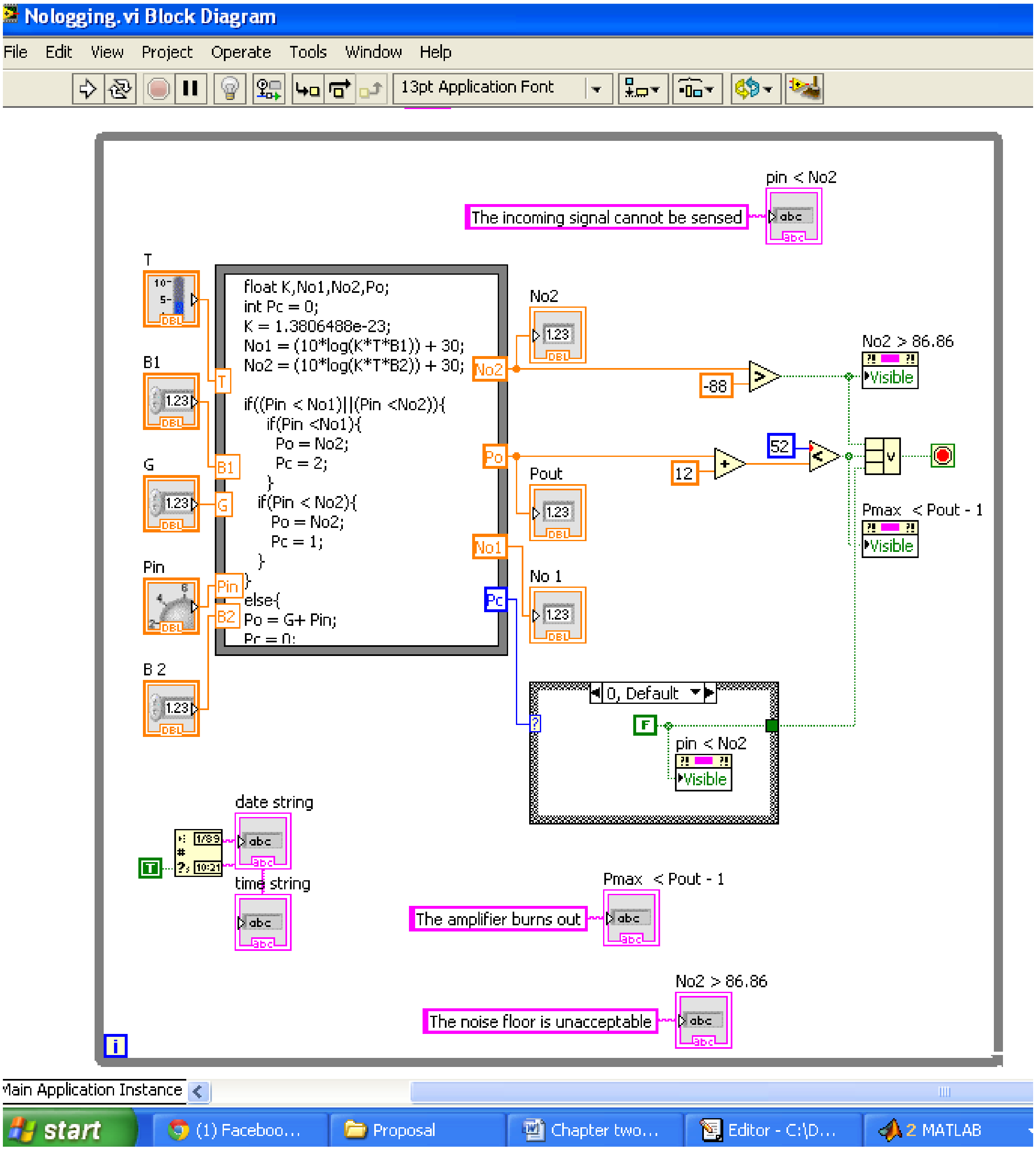
$$10\log\left(\frac{P_{out}}{P_{in}}\right) = 16$$

$$\log\left(\frac{P_{out}}{P_{in}}\right) = 1.6$$

$$\frac{P_{out}}{P_{in}} = 10^{1.6}$$

$$\frac{P_{out}}{P_{in}} = 40$$

Appendix 2: Block diagram for the GUI



Appendix 3: Matlab code for thermal noise computation

Editor - C:\Documents and Settings\makumi01\Desktop\Matlab\test.m*

File Edit Text Desktop Window Help

```
%%Janvier Kamanzi

%% Writing in a '.xls' file %%

filename = 'filename.xls';                    % name of the file containing the results
                                              % only put the file name if the matlab file
                                                 % is in the same directory as the results file

T_low = 215;                                  % low temperature
T_high = 385;                                 % high temperature
Step = 10;                                    % temperature step

T = T_low:Step:T_high;                        % table with the temperatures

k = 1.380644 * 10^(-23);                      % Boltzmann constant

B1 = 432e+6;                                  % first bandwidth
B2 = 460e+6;                                  % secon bandwidth

No1 = ( 10 * log10(10^3*k * T * B1) ).';      % .' => for tranposing the table
No2 = (10 * log10(10^3*k * T * B2) ).';       % .' => for tranposing the table
T_out = T.';                                  % transposing the temperature table

title = { 'T(K)' 'No1(dBm)' 'No2(dBm' };      % first line of the excel file
results = [ T_out No1 No2 ];                  % the results of the calculations

output = [ title ; num2cell(results) ];       % conversion numerics / table w/ cells
                                              % necessary for writing numbers and text in an excel file

```

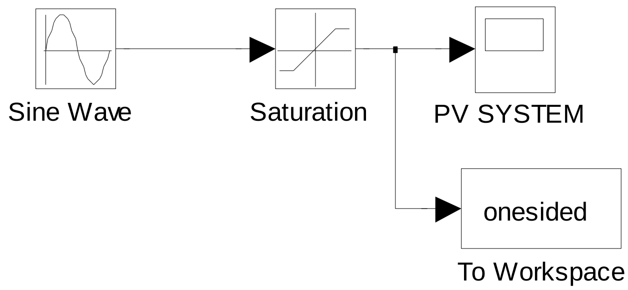
Appendix 4: Matlab code to illustrate thermal noise effects on the LNA

```matlab

clc
clear all
close all
K = 1.380644 * 10^-24;                 %Boltzmann constant
B = 450e6;                             %The upper limit bandwidth
A = zeros(100,9);                      %Creation of an empty array
A(:,1) = 1:100                         %Numbering column
A(:,2) = 2500*rand(100,1);             %Random temperatures in K
A(:,3) = -118.3:1.7:50 ;               %Input signal column
A(:,4) = A(:,3)+16;                    %Output column
A(:,5) = 52;                           %Upper limit output
A(:,6) = 36;                           %Uper limit input
A(:,7) = 40;
A(:,8) = 24;
T = A(:,2);

A(:,5)=(10*log10(K*T*B))+30      %Formula for the noise in dBm

plot(A(:,3),A(:,5), A(:,3),A(:,4),A(:,3),A(:,5),A(:,6),A(:,4))
xlabel('Input power(dBm)')
ylabel('Output power(dBm)')
Title('Thermal effects on the MSP432VDG160-Dynamic range-ideal conditions')
grid on
figure
plot(A(:,3),A(:,5), A(:,3),A(:,4),A(:,3),A(:,7),A(:,8),A(:,4))
xlabel('Input power(dBm)')
ylabel('Output power(dBm)')
Title('Thermal effects on the MSP432VDG160-Dynamic range-Real')
grid on
```

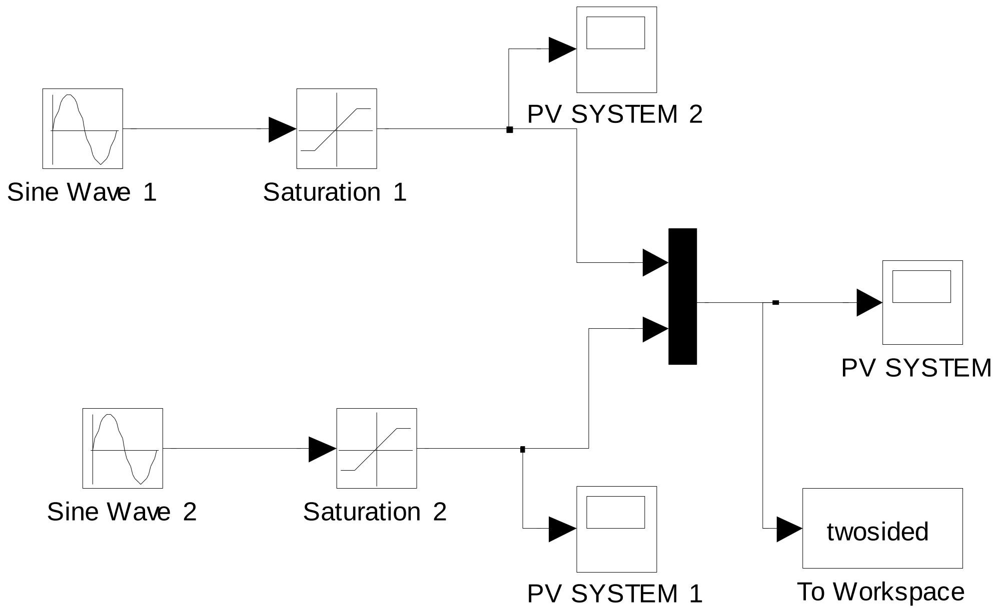
Appendix 5: Matlab code to plot the graphs on the effects of the inclination angles

```
%Janvier Kamanzi, CPUT
%%Irradiance vs the PV inclination angle and the sun's apparent motion
clc
close all
A = zeros(100*pi,8)
A(:,1) = linspace(0,pi,(100*pi))          %phi:Angle for sun's apparent motion
A(:,2) = linspace(0,pi/2,(100*pi))        %theta:Elevation angle
A(:,3) = sin(A(:,1))                      %Effect of the solar radiation incident angle
A(:,4) = sin(A(:,2))                      %Effect of the elevation angle on the irradiance
A(:,5) = A(:,3).*A(:,4)                   %The irradiance with the effects of two angles
A(:,6) = linspace(0,2*pi,(100*pi))
A(:,7) = sin(A(:,6))
A(:,8) = A(:,7).*A(:,4)
plot(A(:,1),A(:,3),'-b',A(:,1),A(:,5),'-.r')
xlabel('angle [rad]')
ylabel('irradiance [kW/m^2]')
title('Irradiance vs PV inclination and sun apparent motion angles')
grid on
figure

plot(A(:,6),A(:,7),'-b',A(:,6),A(:,8),'-.r')

grid on
xlabel('angle [rad]')
ylabel('irradiance [kW/m^2]')
title('Irradiance vs PV inclination and sun apparent motion angles')
Max_sun = max(A(:,3))
Max_sun_elev = max(A(:,5))
```

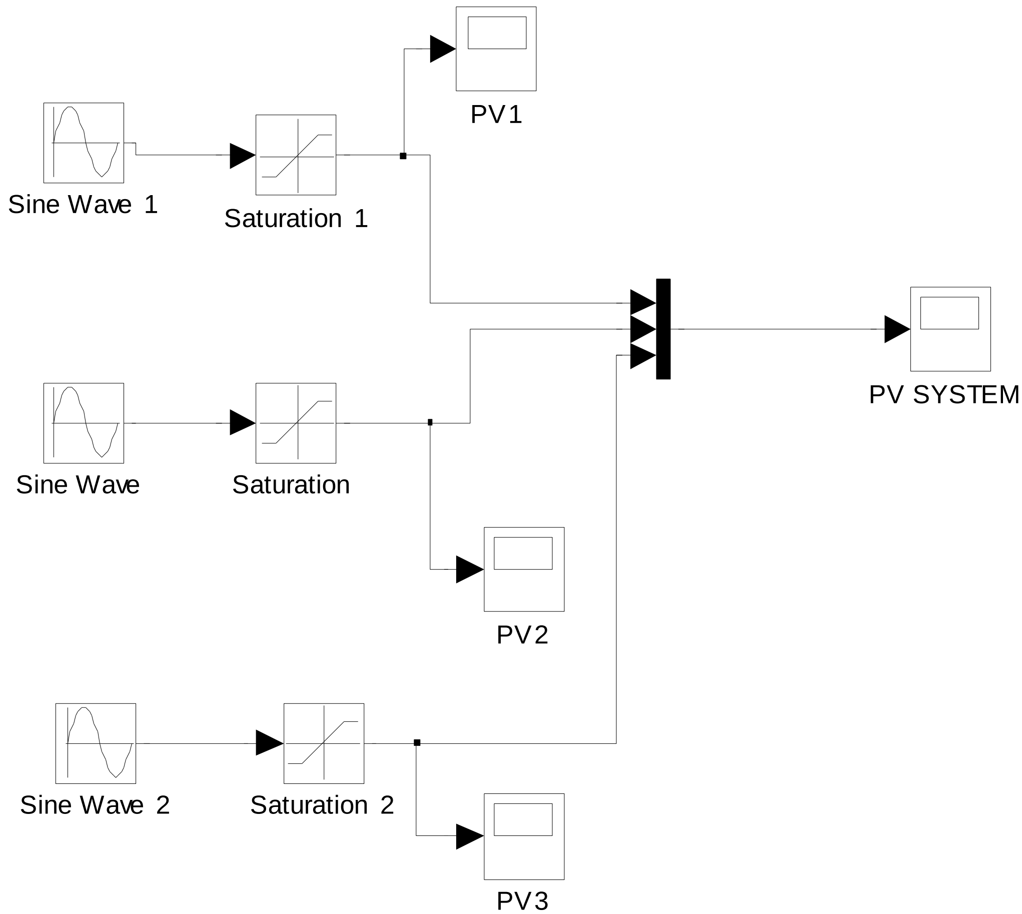
Appendix 6: Single sided topology



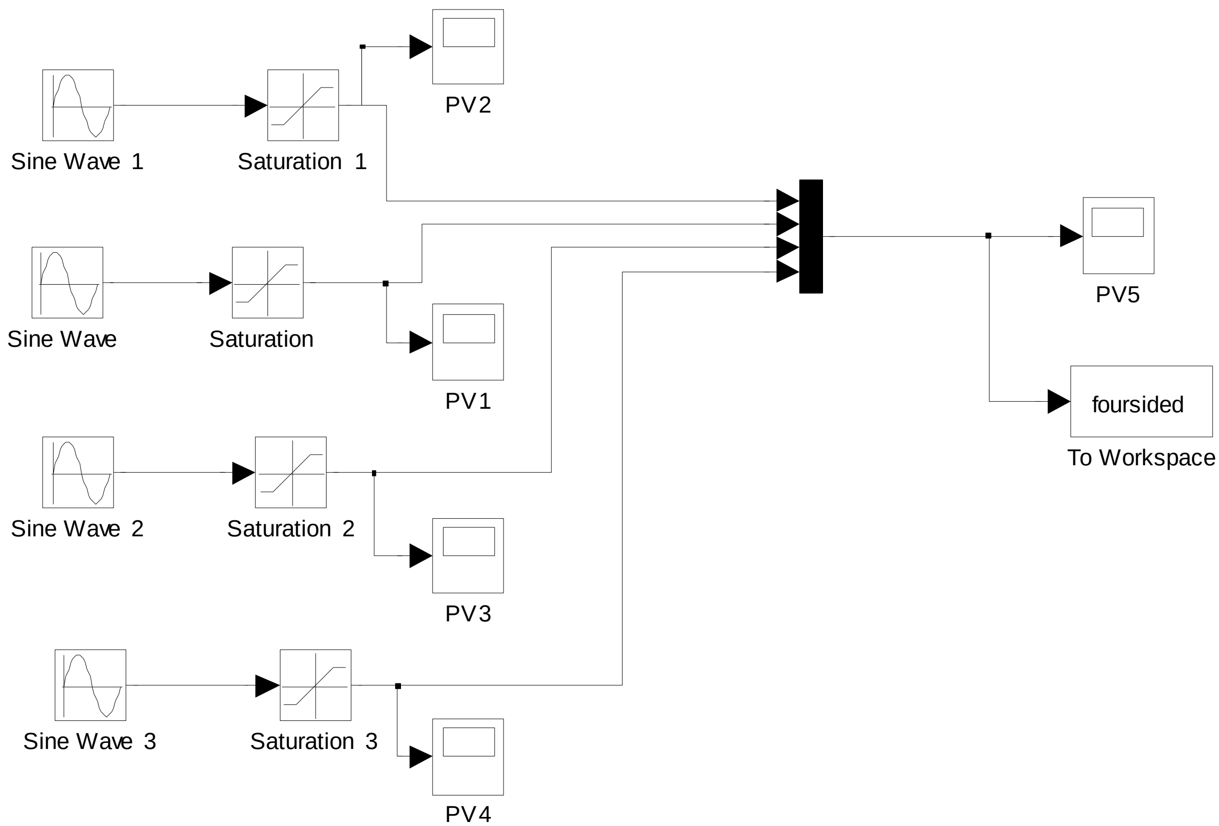
Appendix 7: Double sided topology Simulink model



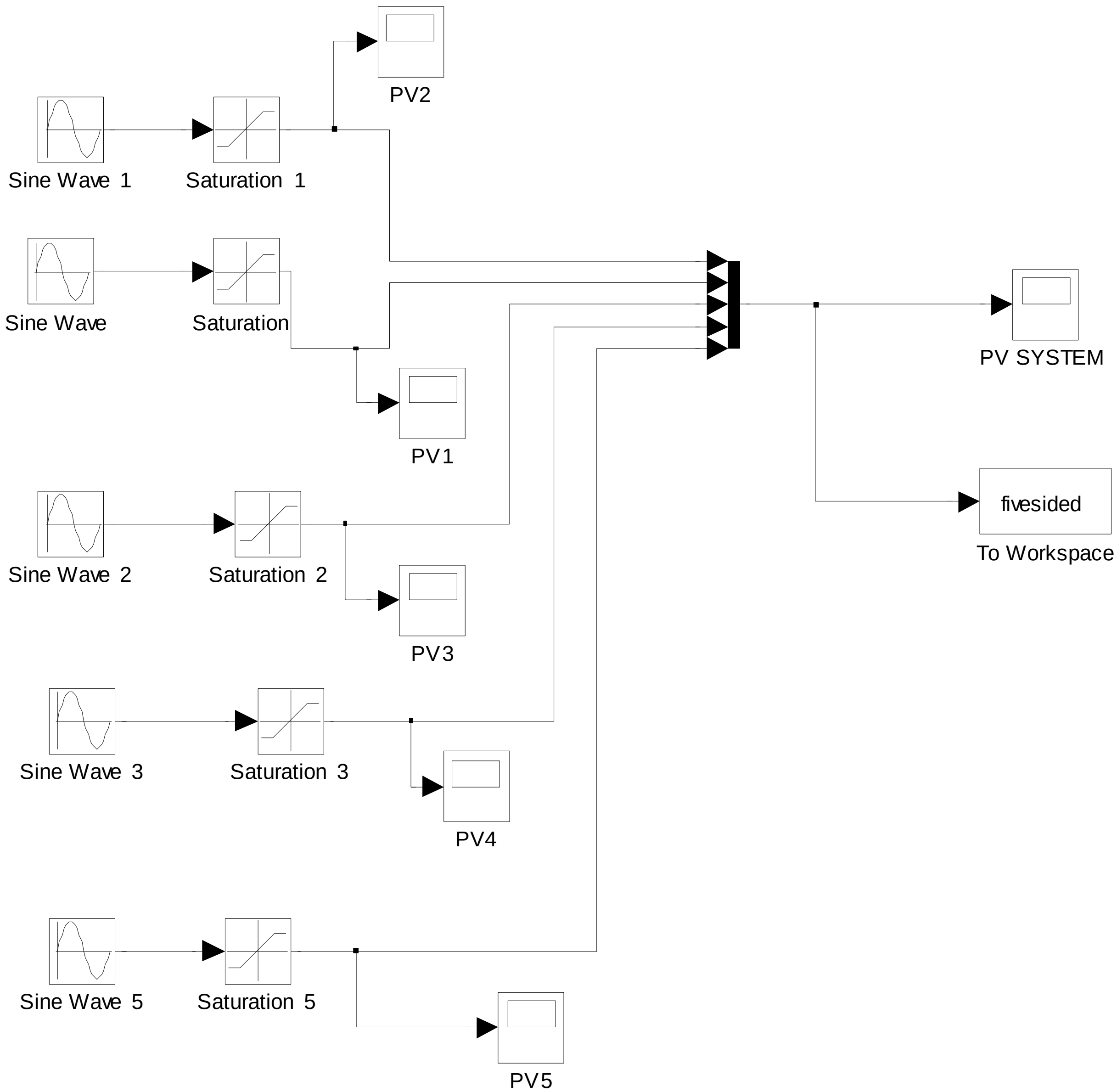
Appendix 8: Three sided pyramid topology simulink model



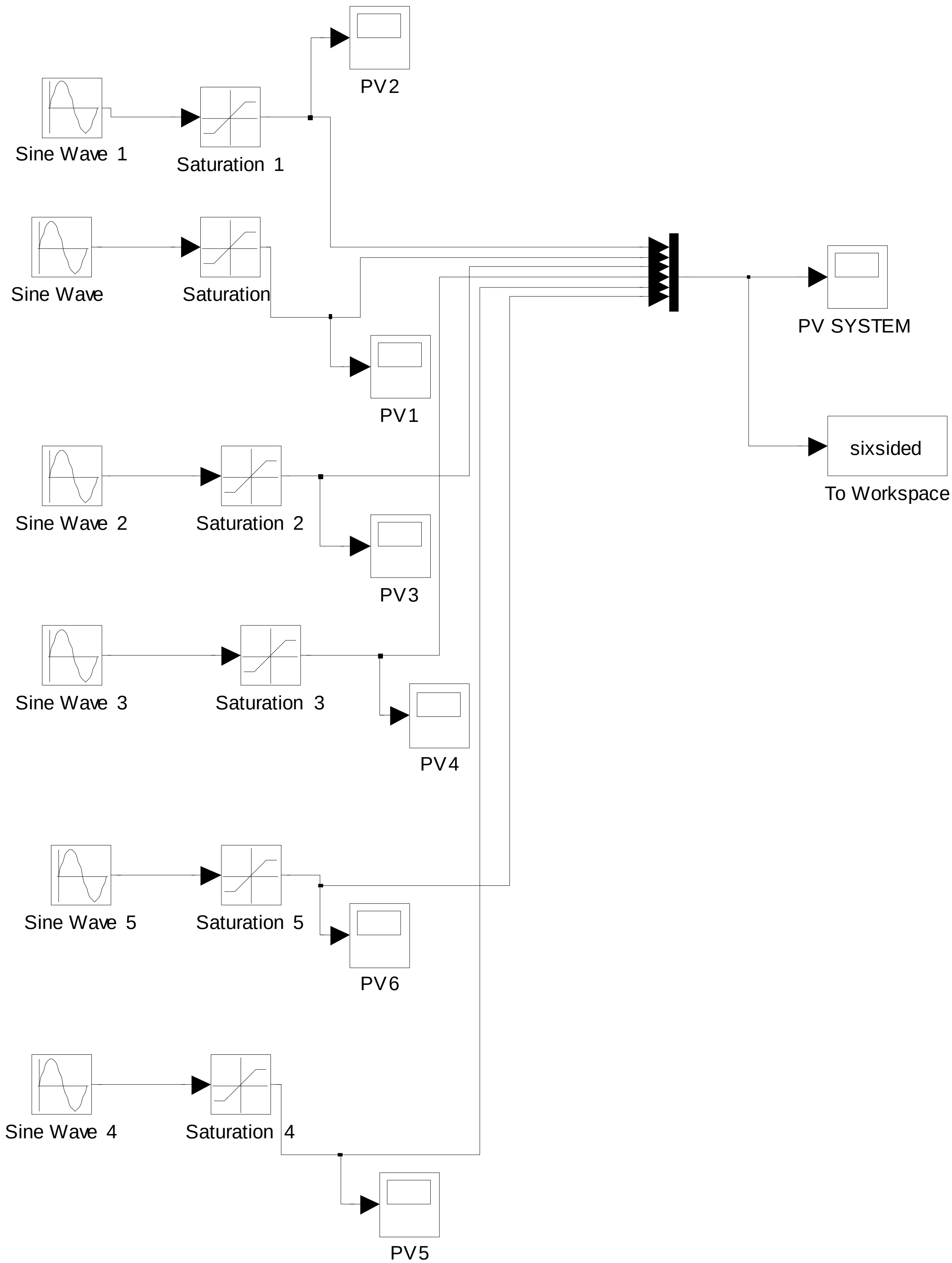
Appendix 9: Four sided pyramid topology simulink model



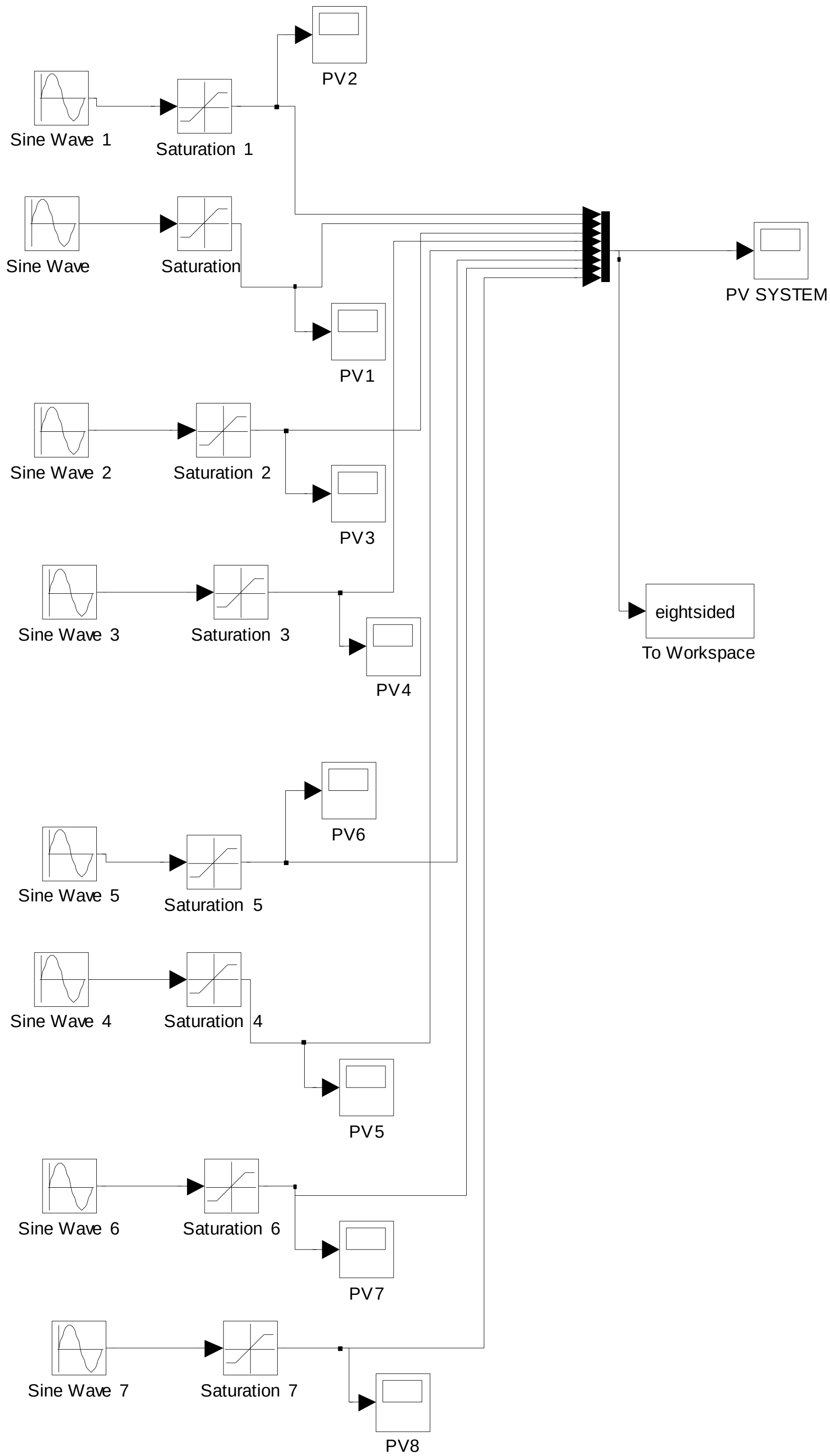
Appendix 10: Five sided pyramid topology simulink model



Appendix 11: Six sided pyramid topology simulink model



Appendix 12: Eight sided pyramid topology simulink model



Appendix 13: Conversion of angles (degrees) into distances (km)

The earth radius = 6,371 km

The circumference = 4, 0030 km

The distance between the equator and the southern pole is (40,030 km)/4 = 10,007 km

In terms of degrees, the same distance is estimated at 360˚/4 = 90˚

Therefore 1 degree corresponds to (10,007 km)/4 ~= 112 km