Chapter 1: Introduction

1.1. Motivation

World energy demand is increasing continuously, and it is expected to grow multiple times by 2040 [1]. It is because the population, as well as their standard of living in developing countries, is growing. The need to come up with sources of green energy for sustainable development has emerged to provide the society with comfort, shelter and future security [1-2].

In the energy system, sources providing baseload capacity are of higher importance in grid integration than the sources providing only peak load demand [2]. Unfortunately, most of the renewable energy sources being utilized for electrical energy conversion have irregular power production, and thus they require additional energy storage units [2]. Recently, most of the industry and institutional work is focused on the adoption of terrestrial solar energy. Researches are going on, and both solar photovoltaic and solar thermal power stations are being used for either distributed power generation or grid integration [3]. However, there are many challenges in the implementation of terrestrial solar energy. For example, solar photovoltaic and solar thermal can supply power only in the daytime, and solar irradiance fluctuates all day, and it fades on cloudy or stormy days. A major problem with solar panels or solar thermal energy is that it needs regular care and maintenance. In solar photovoltaics, it is a key issue because pollution and dirt can degrade photovoltaic efficiency or electrical power production [1-3].

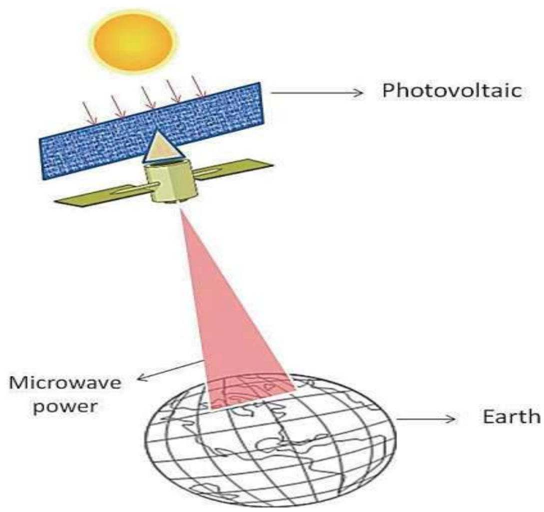


Figure 1. 1 satellite solar power station (SSPS) [1]

On the other hand, among the available renewable energy resources, satellite solar power station (SSPS) is most promising as it can provide 24-hour energy supply [4]. Therefore, it is a suitable for promoting sustainable development of humankind as a green energy source. It assures a carbon dioxide-free energy, convenient for continuous power supply or baseload supply [2, 4]. There are several advantages which have propelled investigation into SSPS to modernize the grid [5]. In SSPS, there is no hindrance to the solar flux by the surrounding atmosphere of the earth as shown in Figure 1. 1. An SSPS constitutes a technique for collecting space solar power utilizing satellites and transporting it to the ground wirelessly by utilization of microwaves [6]. In many aspects, SSPS has advantages over terrestrial solar power due to unobstructed and undistorted solar irradiance available in space [7]. Furthermore, the SSPS has three times more power accessibility over the terrestrial solar power system [7].

There are many key issues for practical implementation of SSPS [1, 8-11]. As SSPS aims for sending high power wirelessly for large distances [1, 8-11]. Wireless power transfer (WPT) for a large distance, i.e., from geosynchronous equatorial orbit (GEO) to earth (36000 km) is a challenging task, but using Gaussian beamforming technique the transmission is possible [11-15]. In SSPS, research should also focus on the reduction of space segment's components dimension and space vehicle dispatch cost [13]. Also, SSPS total system cost reduction is desirable, and therefore an economic model of the system is required. In this thesis, the economic model of SSPS is developed, and it has interrelated parameters which can be optimized for the high efficiency and cost-effective performance [13, 15-18]. In SSPS, a cost minimization method for cost reduction of SSPS is derived, and results are investigated for an economical prototype design. In the space section, the optimal size of transmitting antenna is determined for the desired power density on the receiving ground antenna. According to microwave safety and security limit, microwave power density in earth atmosphere must be below 100 W/m^2 [17]. At frequency 2.45 GHz and 5.8 GHz, the Levelized cost of energy (LCOE) of SSPS is also calculated for the different power capacities.

In SSPS and WPT, the rectenna (antenna and rectifier) is an elementary part for receiving radio frequency (RF) energy and converting RF energy into direct current (DC) power [18-20]. There are many novel rectennas designed at operating frequencies of 2.45 GHz & 5.8 GHz, these are found to be suitable frequencies considering SSPS design [21-23]. In this thesis, linearized circuit model of the rectenna is developed and analysis is performed. An efficient microstrip circular polarized rectenna is designed to operate at 2.45 GHz. Furthermore, unlike the traditional rectenna, a new circularly polarized (CP) microstrip antenna with embedded slots is proposed which can connect to rectifying circuit without harmonics filter. The designed antenna is then connected to rectifying circuit in two ways. One is conventional single source fed rectenna (SSFR), and other is proposed differential source fed rectenna (DSFR). For the comparison, an SSFR and a DSFR are fabricated and tested, RF to DC conversion efficiency of DSFR has been found to be higher than SSFR. Furthermore, an enhanced rectenna with differentially fed antenna array is developed. Firstly, a linear antenna array is designed considering its side lobes less than -20 dB. Then two antenna arrays, one with a single feed and other with differential feed are designed to operate at 5.8 GHz and are tested for RF-DC conversion. It has been observed that the differentially fed rectenna has higher output DC power than the single fed rectenna. Furthermore harmonic harvester Rectenna integrated power management circuitry for improving RF-DC power conversion efficiency is developed. The circuitry is designed for battery charging or energy storage applications; resistance emulation method is used to realize a matching load resistance at output terminals. The proposed technique is useful for harvesting maximum output power from both fundamental and harmonics rectifiers. Also, it delivers the combined maximum power to the energy storage cell. The power management module based on dual input buck-boost converter with simple open-loop control is proposed.

1.1.1. SSPS as base-load power plants

There is a need of base-load power plants to fulfill the rising energy demand. Terrestrial solar power is a clean source of intermittent power supply, yet it is not applicable for base-load power [1-2]. A prominent advantage of SSPS technology over terrestrial solar is that it can be used for base-load power supply [1].

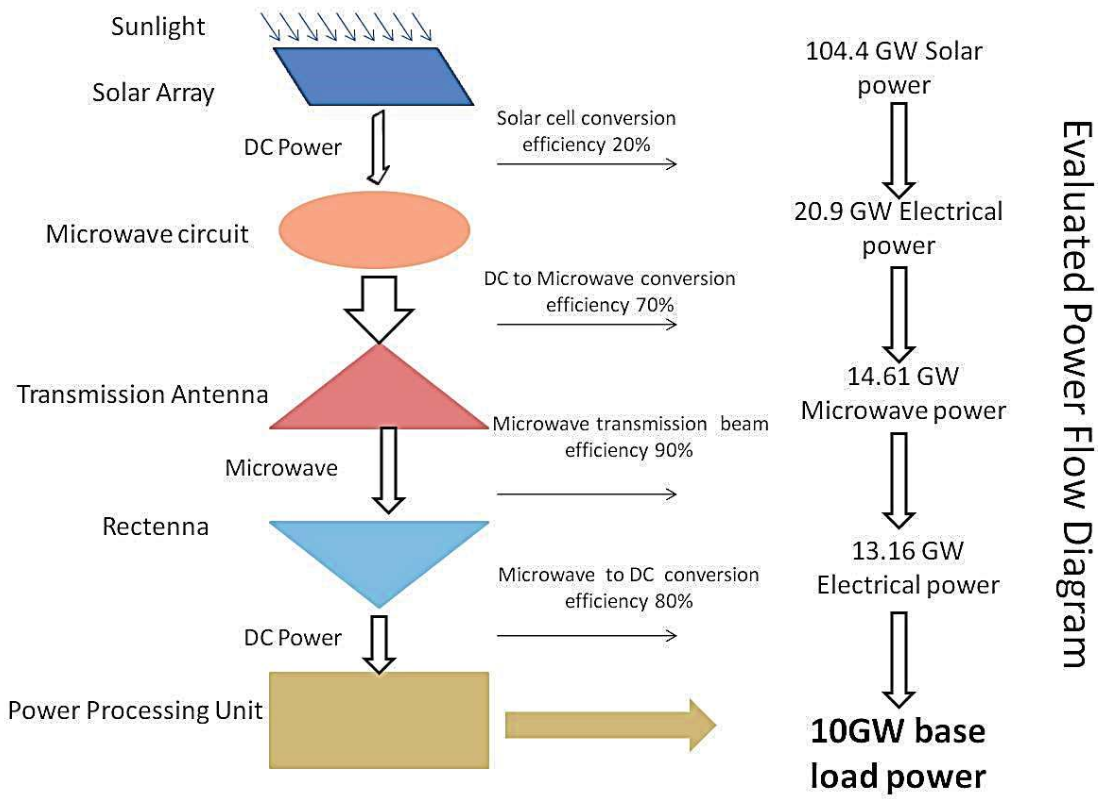


Figure 1. 2 A 10 GW SSPS baseload plant model [29]

For providing base-load power, it is required to place a large satellite in the geosynchronous orbit. However, this idea is full of technical challenges as the SSPS is gigantic and its estimated operation time is about 30 years only. Therefore, its cost can't be evaluated with the present day technology and space transportation system [1, 21]. As a prerequisite two types of space vehicles have to be developed: one for the transportation and one for assembling the SSPS. Reusable Launch Vehicle will transport SSPS segments to a low earth orbit. It will use minimum energy and transportation cost, and further assembly will be performed in this orbit [1, 21-23]. After assembling, an Orbital Dispatch Vehicle will be required to raise the SSPS from the low earth orbit to GEO orbit.

At present, space vehicle transport technology has been contemplated without any consideration for SSPS systems. Therefore, there are requirements for 3rd generation Reusable Launch Vehicles aiming for SSPS. There is also a requirement of large size rectenna on Earth to receive power from space [1]. Land covered under the rectenna could be utilized for agriculture and different purposes [24-27]. With technological advancement, SSPS power cost could be comparable or less than various conventional terrestrial energy sources like coal-based, hydro, nuclear, etc [1].

A 10 GW SSPS baseload plant model is shown in Figure 1. 2. The reference framework was chosen by the USA space research agency (NASA and US DOE 1978). In this system, space satellites collect solar irradiance and photovoltaic transform the solar power into electrical power (DC power) [29-32]. The high voltage DC power is then supplied to microwave generators, i.e., magnetron which delivers the microwave power [26, 29]. The beam formation is achievable using phased array antenna or slotted waveguides [22]. In this way, the electrical power changes into the microwave and after beamforming this microwave power is transferred to a rectenna on the ground station. The receiving microwave antenna connected with rectifier changes the high-frequency microwave power back to electrical power. This way, the space energy is obtainable on earth to supply the commercial grid after appropriate power conditioning [1]. In this model, the 100 km^2 solar array is required for collecting 104.4 GW of space solar insolation at power density of 1370 W/m^2 at geostationary orbit and produces 20.9 GW DC power (20 % conversion efficiency). With Microwave to DC conversion efficiency of 70%, 14.61 GW microwave power will be transmitted from space antenna. By considering 90% beam efficiency at 2.45 GHz, microwave power of 13.16 GW will be available at ground rectenna. If 10 dB Gaussian tapered beam is considered at the receiving rectenna on the earth, a 10 km^2 ground rectenna is required to produce 10 GW electrical DC power (87% power collection efficiency). The SSPS ground rectenna would have 100 million components in array structure with components separated by more than 0.5λ [13, 20]. This power is delivered to the utility grid.

1.2. Literature review

1.2.1. SSPS research worldwide

The principal idea of SSPS was proposed by P.E.Glaser in the year 1968 [1-2, 28]. Following Glaser, USA did extensive research in feasibility scope of SSPS during 1978-80 [28]. This feasibility study was a collaborative effort of National Aeronautics and Space Administration (NASA) and Department of Energy (DOE). Both jointly suggested an enhanced model well-known as a reference model in the year 1979 which proposed a 5 GW SSPS baseload power plant; it is shown in Figure 1. 3 [7].

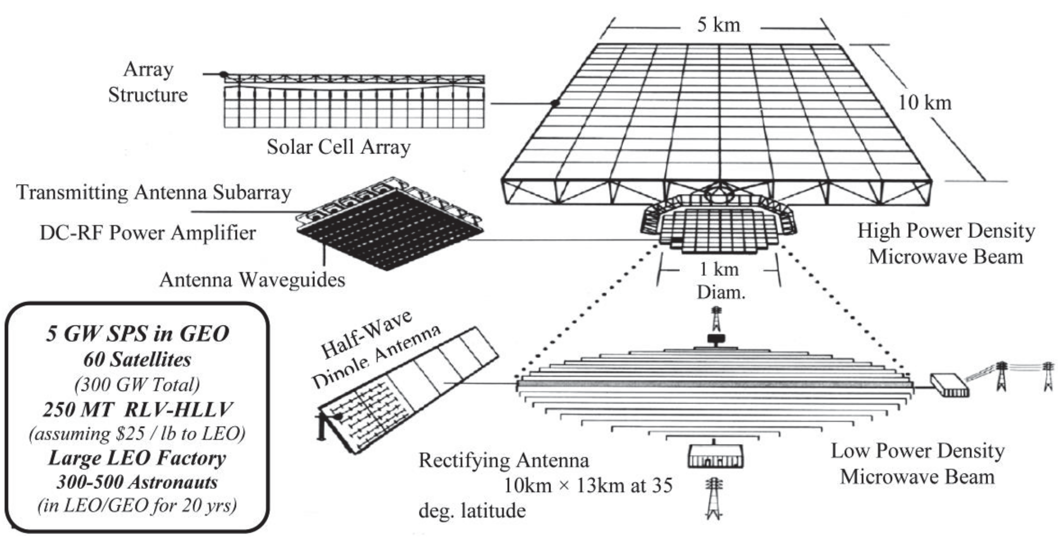


Figure 1. 3 1979 SSPS Reference System Concept (GEO) [7]

The SSPS exploration was kept in abeyance in the USA in the year 1980 due to its high budget. In the progression of the SSPS concept, the "Fresh Look" Space-based Solar Power idea was proposed in the year 1997 as an enhanced SSPS reference model [29], this Sun Tower SSPS model is shown in Figure 1. 4. It was the best design which proposed various innovative techniques that dealt with SSPS advancement.

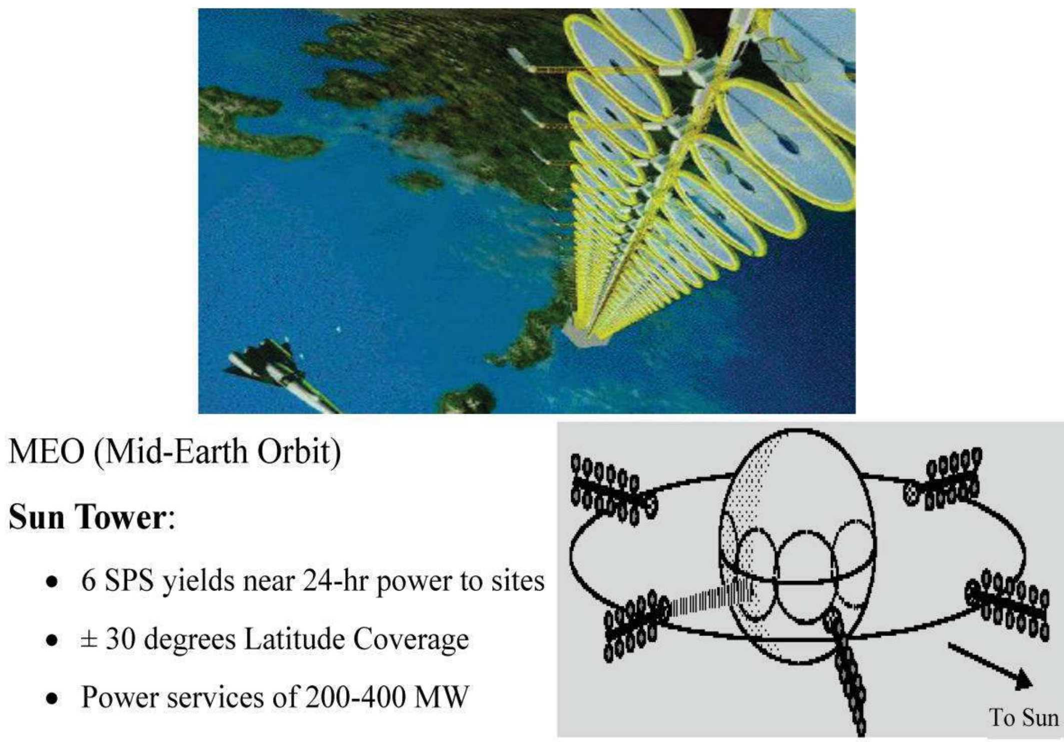


Figure 1. 4 Sun Tower based SSPS model from NASA's 1995-1997 Fresh Look Study [29]

The above-mentioned Sun Tower based SSPS model was based on satellites of standard size, which were simply connected in a balanced structure. It had an inbuilt microwave generator and transmitter [1, 29]. Each satellite looked like a large sunflower directed towards earth. In the structure, the petals exhibit transmitter arrangements and the leaflets on the trail are solar power accumulators. This model proposed six satellites constellation in the low earth orbit (LEO) orbit (900 km altitude) which resembled sun-synchronous condition to deliver 200 MW power on earth continuously. It was expected to transfer microwave energy at frequency 2.45 GHz or 5.8 GHz. On account of the microwave transmitter, heat removal is considered at the rear plane of the antenna cluster [29].

(a) **(b)** **(c)**

Figure 1. 5 (a) Integrated with the symmetrical concentrator. (b) Unmanned Space Experiment Free Flyer (USEF) proposed a tethered model of SSPS. (c) Thin film solar based model [1]

A model, integrated with the symmetric concentrator, as shown in Figure 1. 5(a), was proposed with high solar collection efficiency [30]. In this model, two giant similar clam shells consist of mirrors. Every planar mirror is around 400 meters apart. The structure was build up on the rear plane side at a marginally distinctive point to shape a fragmented clamshell mirror [1, 30]. The mirror's reflection of sunlight is required to be focused only on the solar PV array. An underlying integrated structure on the solar collector provides the design flexibility of placing transmitters on the rear plane of PV arrays. In this way, power cabling separations are highly reduced, and the rear sides of either the solar array or the microwave transmitter structure can be used for radiating heat.

The JAXA (Japan Aerospace Exploration Agency) unit is working on SSPS prototype design and has assessed feasibility at various constituents levels [28]. They suggest that it is plausible to beam microwave power and transfer it to earth. In the year 2001, JAXA proposed a 1 GW SSPS model utilizing microwave transmission at the 5.8GHz frequency. A variety of designs have been technically revised and practically demonstrated. These are not quite the same as the NASA/DOE model [28, 30-35]. While concerning SSPS heat-related problems, an improved structure must contain both the solar array and the transmitting antenna on the same plane. Here, solar arrays and transmission antenna exist collectively on the front surface with alternate arrangement [31]. The rear cover is fully available for heat dissipation, as shown in Figure 1. 5.

Later on, the Institute for Unmanned Space Experiment Free Flyer (USEF) proposed a tethered model of SSPS as shown in Figure 1. 5 (b) [1, 28, 37]. This model was not efficient in sun tracking, and the average power production was reduced by 35% compared to the NASA/DOE reference design [7]. Also, sunlight concentrator was not used with solar collectors that had a negative impact. Furthermore, a large section of the surface is required for collecting sunlight. The only positive point was that the heat was dissipated efficiently into space [37]. Furthermore, a thin film PV array utilized SSPS model was proposed which is shown in Figure 1. 5 (c).

1.2.2. Literature Survey of Rectenna

Rectenna was first produced by Raytheon Company in the year 1963; It was fabricated and tested by R.H George as shown in Figure 1. 6 [28, 38-42]. This design used 28 dipoles which were connected individually to bridge rectifiers. Its power capacity was only 7W, and RF to DC conversion Efficiency was 40%. Later on by utilizing Impedance matching the output power was increased to 270 W [38-44].

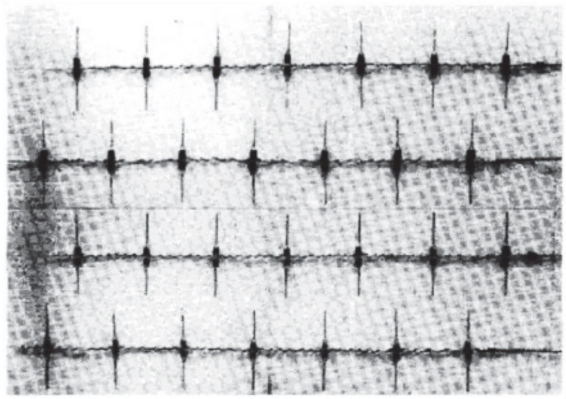
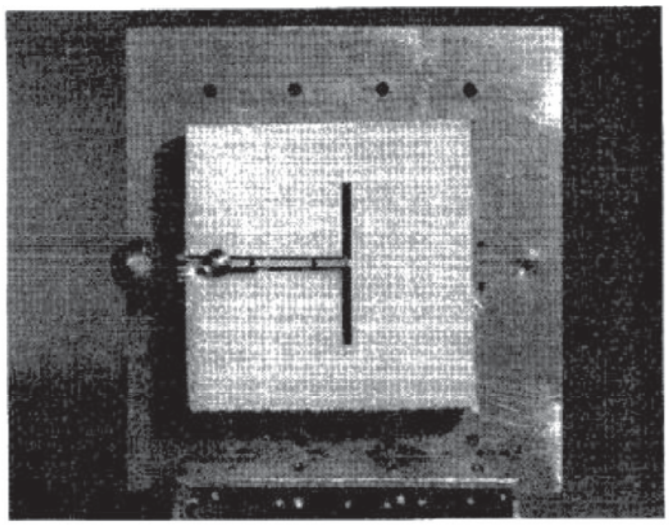


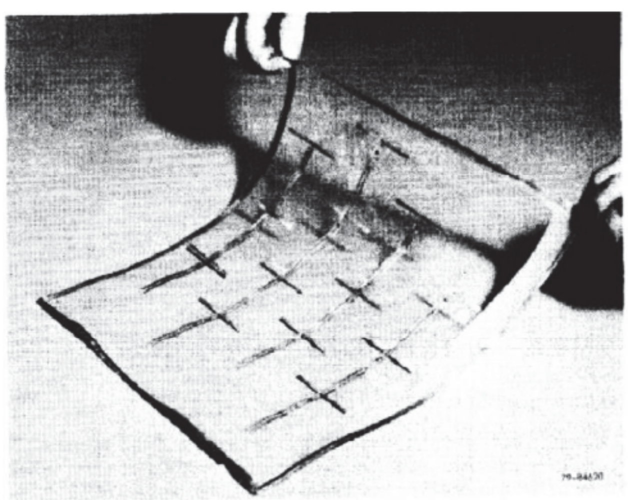
Figure 1. 6 view of the first rectenna made by Raytheon Co. (1963) [28]

In the following years, the size of rectenna was reduced by increasing the operating frequency; many dipole rectennas were developed at 2.45 GHz, it is shown in Figure 1. 7. In 1977 W.C Brown coined the term “Rectenna,” for the Rectifier and Antenna combination [23-24]. He developed a rectenna using GaAs Schottky Diode which achieved a record efficiency of 90.6%. The reason behind using 2.45 GHz working frequency for Microwave power transmission is that it lies in the Industrial Scientific and Medical (ISM) band which is in the atmospheric Window [44]. At this frequency, propagation attenuation is minimum in the atmosphere. In subsequent years APCP Power Technology developed a Rectenna at working frequency of 35 GHz, as it was in the atmospheric window too and reduced the system size. However, transmission components became too expensive and inefficient at the time [28, 38-42].

The working frequency of 5.8 GHz was also found to be suitable for wireless power transmission and was investigated by various organizations. Without sacrificing efficiency and increasing the cost of the system, the designs at 5.8 GHz were found to have an appreciable reduction of system size [21-27].



(a) A rectenna element above a reflecting plane [28]



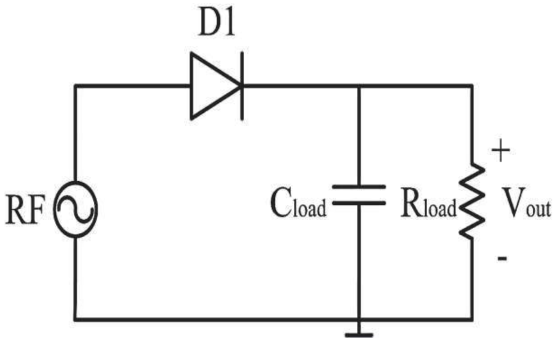
(b) A rectenna fore-plane made in the new thin film etched- circuit format (1982).[28]

Figure 1. 7 some early rectennas [28]

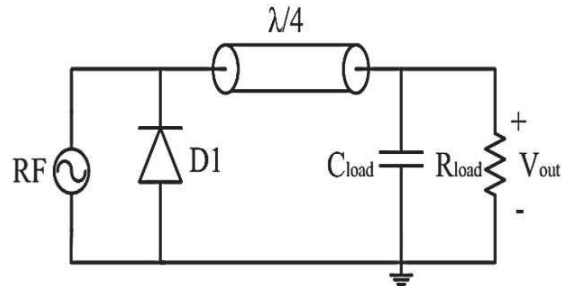
In 1991, W.C Brown investigated low power RF-DC conversion also known as RF energy harvesting. It had various applications like sensors, RFID and as a substitute for batteries and solar cells. Low power Rectenna could harvest electrical energy from ambient RF energy [23, 28].

Individual rectenna has low power capacity. Thus rectenna array is required for significant wireless power transmission. Researches are being done for the development of rectenna and rectenna array [21]. Many types of antennas were proposed in the literature, such as dipoles, yagi-uda antennas, microstrip patch antenna, a spiral antenna, slot antenna. Rectifiers like single shunt rectifier, voltage doubler rectifier, full wave bridge rectifier, the hybrid rectifier can be used for developing Rectennas [21-27].

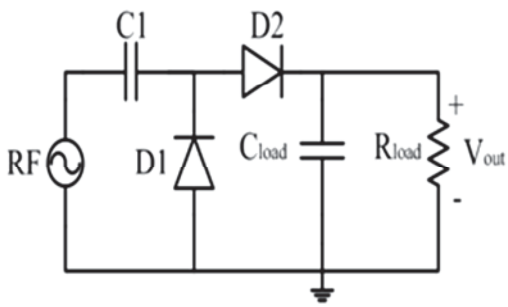
The Schottky Diode based rectifier circuits are most commonly used to convert RF energy into DC [45]. There are multiple methods of doing this, and different rectifier circuit topologies were proposed for efficient rectification [59]. Several circuit topologies have been shown in Figure 1. 8. In The SSSP community typically uses cost-effective and efficient rectenna-based designs as high conversion efficiency is desired and large power densities are available [54]. On the other hand, ambient RF energy harvesting designers and the RFID community utilize charge pump topologies for RF-DC conversion [24].



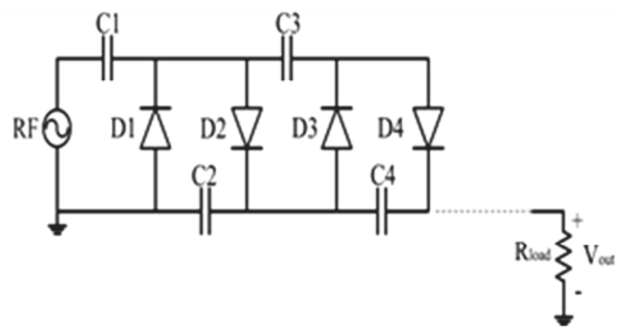
(a) Half- wave rectifier



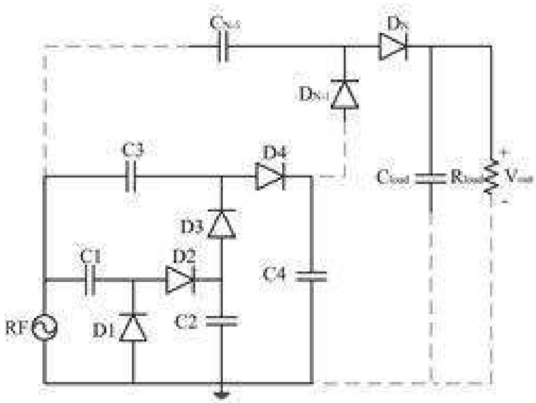
(b) Single Shunt Rectenna



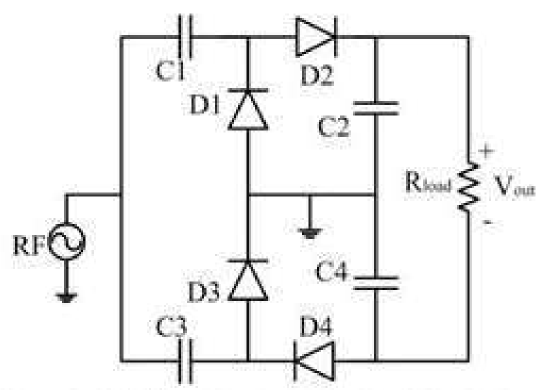
(c) Single stage voltage multiplier



(d) Villard charge pump



(e) Dickson charge pump



(f) Modified Cockcroft-Walton charge pump

Figure 1. 8 (a) Half- wave rectifier (b) Single Shunt Rectenna (c) Single stage voltage multiplier (d) Villard charge pump (e) Dickson charge pump (f) Modified Cockcroft-Walton charge pump [10]

1.3. Thesis outline

This thesis presents a variety of topics, including various key challenges of SSPS, cost minimization strategy of SSPS, single source fed and differential source fed rectenna, differentially fed antenna array connected to the rectifier, rectenna with power management circuitry. SSPS large distance wireless power transfer has been explored, and economic model of SSPS has been presented. In the SSPS ground section a large size rectenna array is required therefore various rectennas are developed, and suitable power management techniques are used for energy storage application.

`The thesis consists of seven chapters. In chapter 2, concept and features of SSPS is presented, and various key issues of SSPS are explored. Microwave power transfer is essential for SSPS, and to be economically feasible high beam efficiency is required. With the efforts of Space agencies worldwide, many of technical issues in SSPS implementation has been resolved successfully, and it is found that SSPS has a high priority of social acceptance. However, the space launch cost (around 15000 $/ kg) is very high at present. It is expected that by the year 2040, it will be reduced by a factor of 1000 (150$/kg) and the SSPS will come into action. Here, least cost derivation for SSPS is also proposed. In Space section, transmitting antenna size reduction is possible utilizing optimized interrelated parameters of the system components. At the receiving antenna, microwave power density (100 w/m^2) is considered, and the minimum SSPS prototype cost is derived at 2.45 GHz and 5.8 GHz. In the cost vs. frequency analysis, it is found to be inversely proportional. The initial cost/kW with the addition of space launch cost/kW is determined for LCOE evaluation; the LCOE value decreases initially then saturates with power variation. At 5.8 GHz and 2.45 GHz, it saturates after 3 GW and 10 GW respectively. It should be noticed here that SSPS with higher power capacity is economically beneficial.

In chapter 3, circuit analysis of rectenna is presented. Furthermore, A circularly polarized (CP) truncated patch antenna with the compact microstrip resonant cell (CMRC) is proposed. Here CMRC is used to reduce the size of rectenna. The CP truncated patch antenna has a maximum gain of 3.07 dBi at the fundamental resonant frequency, i.e., 2.45 GHz. The circular polarization 3 dB axial ratio bandwidth is from 2.419 GHz to 2.461 GHz frequency that is found to be 42 MHz, with the minimum axial ratio of 1.23 dB. The RF-DC conversion efficiency reaches 36.75 % at 10 dBm input power which is independent of the positioning arrangement between the transmitting and receiving antenna.

In chapter 4, a new rectenna is provided with differential source feeding scheme for the low cost and efficient RF-DC conversion. First, a microstrip antenna with a diametrically opposite peripheral projection of isosceles right triangle shape which provides CP is designed. The antenna has four internal slots that are deliberately made to suppress higher order harmonics and enhance fundamental resonance mode. To show it's harmonics rejection capacity, a conventional linearly polarized (LP) circular patch antenna without slots [16] is also designed and fabricated at 2.45 GHz, and their return loss results are compared. The performance of the proposed antenna is verified by the measurement results, such as radiation pattern and return loss. The designed antenna is then tested for RF energy harvesting in two ways. One is conventional SSFR, and other is new DSFR. In the DSFR, the designed antennas are differentially operated by making a difference of $\lambda g/2$ path length; and the ports are then connected to a differentially driven optimized rectifier circuit. Circuit schematics of the single-driven rectifier and proposed differentially driven rectifier is designed. For the comparison, an SSFR and a DSFR are fabricated and tested. The experimental results verify the performance of the proposed rectenna.

In chapter 5, an improved rectenna with a differentially operated antenna array is proposed for efficient RF energy harvesting. A linear, non-uniform, Dolph-Tchebyscheff antenna array with 6 elements is selected. The spacing between elements is provided in a manner such that each element is excited in the same phase. The arrangement is designed with a consideration of side lobes level is less than -20 dB. For comparison, two antenna array, one with a single feed and other with differential feed is designed and fabricated to operate at 5.8 GHz. The performances of the proposed antennas are verified by the measurement results, such as radiation pattern and return loss. For providing the differential feed, a rat race coupler is also designed and fabricated in Agilent ADS 2011. Then both antennas are tested for RF energy harvesting. The performance of the proposed rectenna is verified by measurement results, such as conversion efficiency, output DC power and also compared with single fed rectenna.

In chapter 6, the technique is proposed that is useful for collecting power from the fundamental and harmonics rectifier and deliver the combined maximal power into energy storage cell. The harmonics harvester Rectenna, which has fundamental rectifier output and harmonics rectifier output terminals, the two terminals are interfaced through switches to connect with the buck-boost converter. The two switches will be controlled such that the emulated resistance for both circuits is equal to their matching load resistance at the output terminal to ensure maximal power transfer.

In chapter 7, conclusions and future perspectives are presented. In this thesis, cost minimization strategy of SSPS is presented. Many new rectennas are designed for cost-effective and highly efficient RF-DC conversion. Rectenna with power management circuitry is also developed for energy storage application. Using rectenna arrays energy can be stored which can be further processed to supply AC grid. The technologies are not only beneficial for point to point wireless power transmission but also they could have many applications in low power, ambient RF energy harvesting or RFID application.

After going through brief introduction and literature review of the research work in this chapter, the SSPS concept and various key issues pertaining to SSPS are presented in the next chapter.