RESEARCH ARTICLE OPEN ACCESS

Wireless Power Transmission Compare and Contrast with the Form of Resonance Frequency, Mutual Inductance and Solar Energy

Md. Saifuddin, Tushar Saha, Monirul Islam, Md. Mujammel Hossain Akhand
Supervised by Assistant Professor, Mr.Ebad Zahir
Department of Electrical and Electronic Engineering, American International University-Bangladesh

ABSTRACT
The topic of the thesis is about the wireless power transmission. The details of wireless power, its several elements, their application and working principles are described here. There are also details description of mutual inductance, resonance frequency and solar energy. As a result of an increase in consumer demand for electronic devices, many researchers have begun to develop technology that could power these electronic devices without the use of wires. Even today's most technologically advanced innovations are bound by a relatively short battery life. Through magnetism, resonance, or microwaves many different avenues exist for research and development in regard to wireless power. We will use our paper as an opportunity to investigate different technologies and review them based on their merits. Consumer devices need to accomplish a task not only cheaply but also safely. This paper will allow a better understanding of the exact science behind wireless power transmission. Also it will show how this science relates to products and their environment.

Keywords - Mutual inductance, resonance frequency, solar energy System, wireless power transfer, power transmission efficiency.

I. INTRODUCTION:

Transmission of electrical energy from one object to another without the use of wires is called wireless power transmission (WPT).Wireless power transmission will ensure that the cell phones, laptops, iPods and other power hungry devices get charged on their own, eliminating the need of plugging them in. Even better, because of WPT some of the devices won't require batteries to operate.

1.2 The Principle behind Wireless Power Transmission:

Wireless power transmission (WPT), these words are simpler said than done. The concept behind this fascinating term is a little complex. If we consider two self resonating copper coils of same resonating frequency with a diameter 20 inches each. One copper wire is connected to the power source (wireless power transmitter), while the other copper wire is connected to the device (wireless power receiver). The electric power from the power source causes the copper coil connected to it to start oscillating at a particular (MHz) frequency. Subsequently, the space around the copper coil gets filled with non-magnetic radiations. This generated magnetic field further transfers the power to the other copper coil connected to the receiver. Since this coil is also of the same frequency, it starts oscillating at the same frequency as the first coil. This is known as 'coupled resonance' and is the principle behind WPT. As a result of an increase in electronics in the last hundred years, many researchers have begun to develop technology that could power these electronic devices without the use of any wires. For many years people have been attempting to find a method of wireless power transfer however only recently has this become a very largely researched topic.

1.3 History of Wireless Power

Wireless power has fallen out of favor in recent times as a means of power distribution. This can be attributed to concerns about its safety and its viability as a means for realistically transferring energy over distances both small and large. The field of wireless energy transfer was much more budding than it is now. During the birth and early development of radio this was a hot field of study and innovation. Scientists at the time had very grandiose plans for how to harness the power of electromagnetic waves for much more than just getting voice or data from point to point. Nikola Tesla is known to many today as the "Godfather of Radio." His contributions to the field are numerous and very important. Tesla Theory is especially important to wireless power transport. His ideas for its uses are especially grandiose, yet they were very futuristic and may even hint at future practical engineering accomplishments. Tesla is an often forgotten member of the engineering community. The eponymous "Tesla Coil" is at the heart of much of his wireless power work. It is not uncommon today to see demonstrations of a Tesla Coil being used to light up an incandescent bulb across a room. A Tesla coil is a special transformer that can take the electricity from your house and convert it rapidly to a great deal of high-voltage, high frequency, and low amperage power.

Figure1.1. Bulbs powered by power lines EMF field.

Tesla faced many practical problems with his ideas that had nothing to do with technical short-comings or poor engineering. Nikola Tesla was faced with many of the problems that accompany a new and potentially capitol-losing endeavor. Throughout most of his career he placed a secondary role to many more famous characters. An employee of Edison for a time, he was promised a large sum of money and worked on some of the companies most difficult problems. In the end however he ended up digging ditches for the company and received none of the $50,000 he was promised. Tesla believed strongly in the merits of AC power while Edison himself thought more of the old standard DC that had been in use longer. Eventually he would move his laboratory and work to a remote site in Colorado Springs. This allowed his plenty of space to experiment. It is here where he did most of the research and development for what eventually became known as wireless power transport. He saw wireless power as a commercially viable system of distributing power. He saw a modified Tesla Coil as a better "grid" or central system for distributing power to the masses. The lack of a physical distribution medium would mean less loss in transport. Even today our most efficient means of distributing power has only an efficiency of around 75%. Tesla claimed that his system would allow for up to 95% efficiency due to the lack of mass and therefore resistance that it must travel through [23]. To finance such a huge project he turned towards the premier source of capitol at the time in J.P. Morgan. He was given $150,000 dollars to develop a system of delivering power. The result of this capitol and the hard work of Nikola himself was the Wardenclyffe Tower close to Long Island. This tower was also to serve the purpose of hosting trans-Atlantic communication and also broadcasting duties. The project however was never completed due to funding being pulled [24]. It is easy to see that this is one of the major early defeats that befell wireless power. Tesla began a long slow steady descent into mental illness that was not commonly known at the time. He was not treated properly and ended up suffering from several breakdowns and a severe case of obsessive-compulsive disorder. Tesla however did not see his work as a waste of time or a bad idea. "My project was retarded by laws of nature. The world was not prepared for it. It was too far ahead of time." [24] But the same laws will prevail in the end and make it a triumphal success." In this quote he shows his innovation to be more prophetic than practical in his time. The strange thing is however that his innovation was not a pipe dream at the time, in fact it was fully functional and based on sound mathematical and physical principals. Another event in the history of beamed power that stands above nearly all other is the televised flight of the microwave-powered helicopter. Experts in the field of wireless power liken this to the Wright Brothers flight at Kitty Hawk. It had a monumental effect of demonstrating viability of a certain technology to a whole new group of people, both those in technical fields, but also those of the general public. This demonstration does not show a frivolous Technology with no applications or future. The demonstration was of small helicopter powered by nothing more than the weightless fuel of DC electrical power being beamed invisibly through the air directly to the toy-sized device [23]. Immediate practical uses for this technology were evident. The scale could be increased to create a communication or spy purposes and it could stay stationed for months at a time.

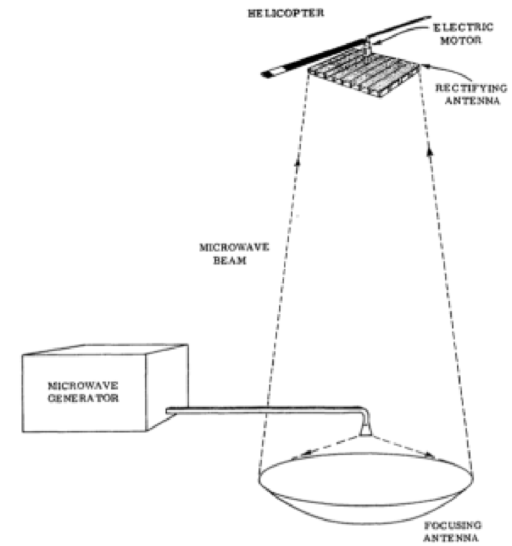


Figure.1.2. Shows principals behind helicopter demonstration

This showing also was an introduction to the technology to those in technical fields. The idea of wireless power was not one that many engineers were well versed in at the time. This showing helped to at least bring it into the consciousness of technical individuals across the globe [23]. The history of wireless power shows us not only failure, but also triumphs of innovation and of wit. With all the failures has come eventual success because of persistence and the advent of media.

1.4 How Wireless Power Could Work:

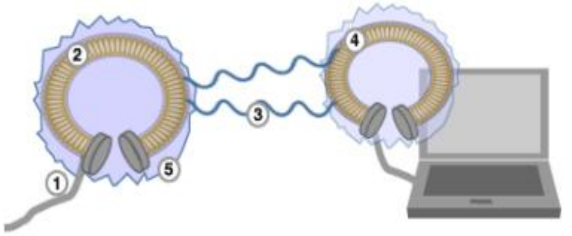


Figure.1.3 Principals of Resonant Power Transfers. [35]

1) Power from mains to antenna, which is made of copper 2) Antenna resonates at a frequency of 6.4MHz, emitting electromagnetic waves 3) Tails of energy from antenna tunnel up to 5m (16.4ft) 4) Electricity picked up by laptop's antenna, which must also be resonating at 6.4MHz.Energy used to re-charge device 5) Energy not transferred to laptop reabsorbed by source antenna. People /other objects not affected as not resonating at 6.4MHz.

1.5 Practical Uses for Wireless Power Transmission:

Innovation cannot stay in a laboratory it must be let out for consumers to purchase and use. Wireless power has long stayed hidden in academia and in research and development labs and is finally, but slowly, making its way into our Homes and offices. Several different companies are attempting to make wireless power a viable product on store shelves. The most prominent of these companies is UK based Splash power. The idea of their product is simple. A "pad" is placed on a table. A cell phone, an MP3 player, or a laptop is placed on top. The products use a special receptor and the pad then uses the principal of induction to send power to the devices battery. This along with a relatively similar process in electric toothbrushes isn't exactly the breakthrough that consumers and engineers are looking for. These devices use a well-known phenomenon and accomplish the same task with very little convenience gained. They still require a very close proximity. This sort of technology is very likely to be all we see from this branch of study for the next five to ten years.[35] We need to look to the future to find out more interesting uses for wireless energy transfer and also look at reasons why it has been looked at so skeptically in the past due to health concerns. First looking at the recent success of Wi-Fi for short-range high-speed data connections. Wi-Fi has exploded due to its low cost and wide market penetration. It is very convenience and has played a huge role in the increase in Internet usage.

II. Objective of this work:

Our main objective is to compare and contrast on wireless power transmission with the form of mutual inductance, resonance frequency and solar energy system, which one will be applicable for Bangladesh.

2.1 Introduction

The thesis work is on wireless power transmission. In this chapter the basic of the term, "Resonance", "Mutual Inductance", Solar Energy" are described in details.

2.2 Study the phenomenon of resonance in RLC circuit

A resonant circuit, also called a tuned circuit consists of an inductor and a capacitor together with a voltage or current source. It is one of the most important circuits used in electronics. For example, a resonant circuit, in one of its many forms, allows us to select a desired radio or television signal from the vast number of signals that are around us at any time.
A network is in resonance when the voltage and current at the network input terminals are in phase and the input impedance of the network is purely resistive.

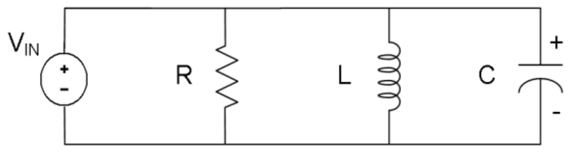


Figure 2.1: Parallel Resonance Circuit

Consider the Parallel RLC circuit of figure 2.1. The steady-state admittance offered by the circuit is:

Y = 1/R + j(ωC – 1/ωL)

Resonance occurs when the voltage and current at the input terminals are in phase. This corresponds to a purely real admittance, so that the necessary condition is given by;

ωC – 1/ωL = 0

The resonant condition may be achieved by adjusting L, C, or ω. Keeping L and C constant, the resonant frequency ωo is given by:

$$w_o = \frac{1}{\sqrt{LC}} \quad \text{rad/s} \qquad (1)$$

OR

$$f_o = \frac{1}{2\pi\sqrt{LC}} \quad \text{Hertz} \qquad (2)$$

2.3 Frequency Response:

It is a plot of the magnitude of output Voltage of a resonance circuit as function of frequency. The response of course starts at zero, reaches a maximum value in the vicinity of the natural resonant frequency, and then drops again to zero as ω becomes infinite. The frequency response is shown in figure 2.2.

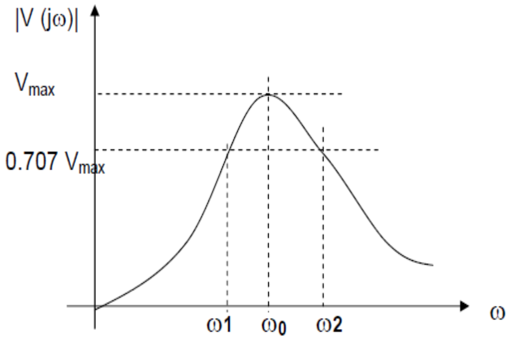


Figure 2.2: Frequency Response of Parallel Resonant Circuit

The two additional frequencies ω1 and ω2 are also indicated which are called half-power frequencies. These frequencies locate those points on the curve at which the voltage response is 1/√2 or 0.707 times the maximum value. They are used to measure the band-width of the response curve. This is called the half-power bandwidth of the resonant circuit and is defined as:

$$\beta = \omega 2 - \omega 1 \qquad (3)$$

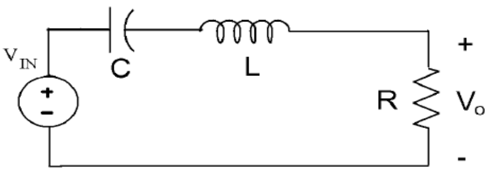


Figure 2.3: Series Resonance Circuit

2.4 Mutual Inductance

Suppose two coils are placed near each other, as shown in Figure 2.4

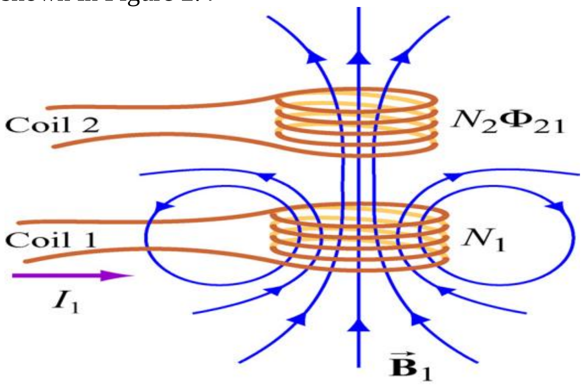


Figure 2.4 changing current in coil 1 produces changing magnetic flux in coil 2

The first coil has N1 turns and carries a current I1 which gives rise to a magnetic field vector B1. Since the two coils are close to each other, some of the magnetic field lines through coil 1 will also pass through coil 2. Let Φ21 denote the magnetic flux through one turn of coil 2 due to I1. Now, by varying I1 with time, there will be an induced emf associated with the changing magnetic flux in the second coil:

$$\varepsilon_{21} = -N_2 \frac{d\Phi_{21}}{dt} = -\frac{d}{dt}\iint_{coil\,2} \vec{B}_1 \cdot d\vec{A}_2 \qquad (11.1.1)$$

The time rate of change of magnetic flux Φ21 in coil 2 is proportional to the time rate of change of the current in coil 1:

$$N_2 \frac{d\Phi_{21}}{dt} = M_{21}\frac{dI_1}{dt} \qquad (11.1.2)$$

where the proportionality constant M21 is called the mutual inductance. It can also be written as

$$M_{21} = \frac{N_2\Phi_{21}}{I_1} \qquad (11.1.3)$$

The SI unit for inductance is the henry (H):

$$1\ \text{henry} = 1\ \text{H} = 1\ \text{T}\cdot\text{m}^2/\text{A} \qquad (11.1.4)$$

We shall see that the mutual inductance M21 depends only on the geometrical properties of the two coils

such as the number of turns and the radii of the two coils.
In a similar manner, suppose instead there is a current I1 in the second coil and it is varying with time (Figure 11.1.2). Then the induced emf in coil 1 becomes

$$\varepsilon_{12} = -N_1 \frac{d\Phi_{12}}{dt} = -\frac{d}{dt} \iint_{\text{coil 1}} \vec{\mathbf{B}}_2 \cdot d\vec{\mathbf{A}}_1 \qquad (11.1.5)$$

and a current is induced in coil 1.

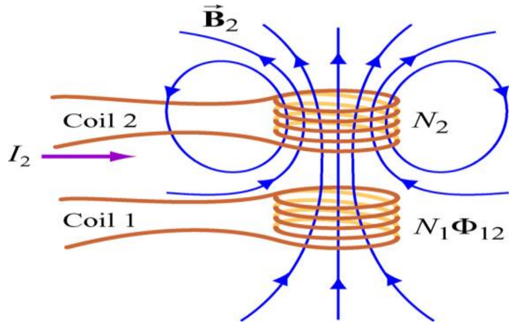


Figure 2.4.1 Changing current in coil 2 produces changing magnetic flux in coil 1.

This changing flux in coil 1 is proportional to the changing current in coil 2,

$$N_1 \frac{d\Phi_{12}}{dt} = M_{12} \frac{dI_2}{dt} \qquad (11.1.6)$$

where the proportionality constant M21 is another mutual inductance and can be written as

$$M_{12} = \frac{N_1 \Phi_{12}}{I_2} \qquad (11.1.7)$$

However, using the reciprocity theorem which combines Ampere's law and the Biot-Savart law, one may show that the constants are equal:

$$M_{12} = M_{21} \equiv M \qquad (11.1.8)$$

2.5 Solar Energy

Solar power cells convert sunlight into electricity, using the energy of speeding photons to create an electrical current within a solar panel. Photons are created in the center of the sun by the fusion of atoms. It takes a photon about a million years to work its way to the surface of the sun, but once free it is hurled through space so fast that it reaches earth in just eight minutes - after traveling 93 million miles. This tremendous energy from the sun is abundant, and has been powering the earth for billions of years - feeding plants, redistributing and refreshing water supplies and ultimately creating other forms of energy (such as fossil fuels) that largely power our civilization today. Over the past several decades, scientists have been learning to harness this ancient energy source with more efficiency to do the work of non-renewable fuels - without pollution, noise or radiation, and not subject to economic whims that drive costs higher each year. An interesting side note: Photons are also called quanta. They are literally "packets" of sunlight". Albert Einstein got his Nobel Prize for his study of quantum mechanics. Solar power panels are made from specially treated semiconductor materials composed mostly of silicon atoms. The panels - also called photovoltaic modules - are constructed with two sheets of silicon manufactured to take advantage of the photons bombarding the earth. One sheet, called the N-layer, is constructed of silicon atoms that have "extra" electrons wandering freely within the layer. The other sheet, called the P-layer, has "missing" electrons, or "holes" that attract free electrons. The two layers are separated by an electrical field, created by the interaction of atoms from both sides. When a photon of sunlight strikes an atom in either layer, it knocks loose an electron. In the P-layer, these free electrons easily cross through the electrical field and into the N-layer. But this movement of electrons is one-way; N-layer electrons aren't able to cross the electrical field into the P-layer. As a result, an excess of free electrons build up in the N-layer. A metal wire attached to the N-layer gives the excess electrons somewhere to go. This circuit ultimately leads back to the P-layer, depositing free electrons where they can begin the process again. Before returning to the P-layer, the electrons are used to power electrical appliances in homes, offices, schools and factories. The movement of electrons with energy is called an electric current. As long as the sun is shining, the electrical current in a solar-electric system continues.

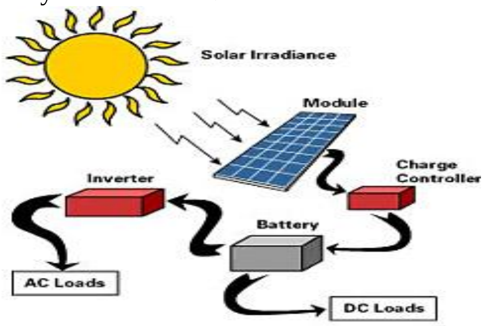


Fig: 2.5 conversion of solar power.

2.6 Solar Panel

A solar panel (photovoltaic module or photovoltaic panel) is a packaged, connected assembly of solar cells, also known as photovoltaic cells. The solar panel can be used as a component of a larger photovoltaic system to generate and supply electricity in commercial and residential applications. Because a single solar panel can produce only a limited amount of power, many installations contain several panels. A photovoltaic system typically includes an array of solar panels, an inverter, and sometimes a battery and interconnection wiring. Solar panels use light energy (photons) from the sun to generate electricity through the photovoltaic effect. The structural (load carrying) member of a module can either be the top layer or the back layer. The majority of modules use wafer-based crystalline silicon cells or thin-film cells based on cadmium telluride or silicon. The conducting wires that take the current off the panels may contain silver, copper or other non-magnetic conductive transition metals. The cells must be connected electrically to one another and to the rest of the system. Cells must also be protected from mechanical damage and moisture. Most solar panels are rigid, but semi-flexible ones are available, based on thin-film cells. Electrical connections are made in series to achieve a desired output voltage and/or in parallel to provide a desired current capability. Separate diodes may be needed to avoid reverse currents, in case of partial or total shading, and at night. The p-n junctions of mono-crystalline silicon cells may have adequate reverse current characteristics that these are not necessary. Reverse currents waste power and can also lead to overheating of shaded cells. Solar cells become less efficient at higher temperatures and installers try to provide good ventilation behind solar panels. Some recent solar panel designs include concentrators in which light is focused by lenses or mirrors onto an array of smaller cells.

This enables the use of cells with a high cost per unit area (such as gallium arsenide) in a cost-effective way. Depending on construction, photovoltaic panels can produce electricity from a range of frequencies of light, But usually cannot cover the entire solar range (specifically, ultraviolet, infrared and low or diffused light). Hence much of the incident sunlight energy is wasted by solar panels, and they can give far higher efficiencies if illuminated with monochromatic light. Therefore, another design concept is to split the light into different wavelength ranges and direct the beams onto different cells tuned to those ranges. This has been projected to be capable of raising efficiency by 50%. Currently the best achieved sunlight conversion rate (solar panel efficiency) is around 21% in commercial products, typically lower than the efficiencies of their cells in isolation. The energy density of a solar panel is the efficiency described in terms of peak power output per unit of surface area, commonly expressed in units of watts per square foot (W/ft2). The most efficient mass-produced solar panels have energy density values of greater than 13 W/ft2 (140 W/m2). Solar power technology is not a recent advent; in fact, it dates back to the mid 1800s to the industrial revolution where solar energy plants were developed to heat water which created steam to drive machinery.

Fig: 2.6.Solar panel

2.7 Solar panel history

In 1839 Alexandre Edmond Becquerel discovered the photovoltaic effect which explains how electricity can be generated from sunlight. He claimed that "shining light on an electrode submerged in a conductive solution would create an electric current." However, even after a lot of research and developments after this discovery, photovoltaic power continued to be very inefficient and photovoltaic cells were used mainly for the purposes of measuring light.

2.8 Summary

In this chapter, the basic terms “Resonance”, “Mutual Inductance”, Solar Energy” are described in details to give a general idea to the readers so that they could understand the thesis easily.

III. Wireless Power Transfer via Magnetic Resonance Using Transmission Coil

3.1 Introduction

A wireless power transfer system via magnetic A wireless power transfer system via magnetic resonance has been worked by several groups [1-3]. Toshiba Corporation has worked about wireless power transmission via magnetic resonance using transmission coil. According to their researches, we reviewed that this system can also be applicable for our country for getting better efficiency. For this system we need two resonance coils work as a transmission coil and a reception coil, respectively. The transfer efficiency between two coils is a function of the distance and the orientation between the coils. When the distance between the two coils is long, the transfer efficiency is small. When two coils share a single axis, the transfer efficiency is maximal, but otherwise the efficiency becomes lower. If their axes are orthogonal and the center of one coil lies on the axis of another, the transfer efficiency becomes minimal. In some applications where the distance and the orientation of the coils are difficult to keep fixed, an appropriate countermeasure against the decline of transfer efficiency is desired. A wireless power transfer system via magnetic resonance using the third coil has been proposed to improve the transfer efficiency [4]. The third coil, which is implemented in the wireless power transfer system, does not need to carry any electrical device such as an amplifier circuit or a rectifier circuit. The proposed system can improve the transfer efficiency when the distance between two coils is large. However, it is required to change the location of the third coil in order to obtain the maximum improvement of the transfer efficiency when the orientation of the coils is not fixed. In this paper, a wireless power transfer system via magnetic resonance using a transmission coil array is proposed to improve the transfer efficiency. The proposed system can improve the transfer efficiency when the receiving coil rotates by any angle. The transmission coils of the coil array are excited with appropriate phase weights by a transmission circuit, according to the orientation among the transmission coils and the receiving coil.

3.2 Configuration of the proposed wireless power transfer system

Fig. 3.1 shows the configuration of the proposed wireless power transfer system using a transmission coil array. The transmission coil array is composed of Transmission Coil 1 and Transmission Coil 2.Transmission Coil 1 and Transmission Coil 2 are put with a distance dt. A reception coil is put away with a distance of d from the center of the transmission coil array. The orientation angle of the reception coil is □. Each coil is induced by a respective loop and the gap between Transmission Coil 1 and the loop is gt1.A gap between Transmission Coil 2 and the loop is gt2.Each loop of the transmission coil is excited by a transmission circuit. The gap between the reception coil and the loop is gr. Input impedance of the transmission circuit and the reception loop are matched to 50 ohms by adjusting the gaps. The field distribution caused by the excitation of the proposed transmission coil array is controlled using different excitation modes of the transmission circuit. The first mode is in-phase excitation and the second mode is out-of-phase excitation. The transfer efficiency is expected to be improved by the choice of an appropriate transmission mode according to the orientation angle of the reception coil.In this work, the shapes of the coils and loops are the same. The parameters of the coils are as follows. The diameter of the oil r1 is 150 mm. he height of the coil h is 30 mm. The diameter of the coil wire is 2.2 mm. The coil is made by winding copper wire.

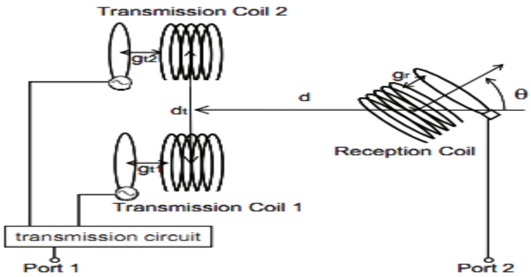
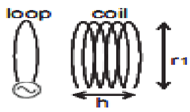


Figure a: Wireless power transfer system using a transmission coil



(b) Structure of coil

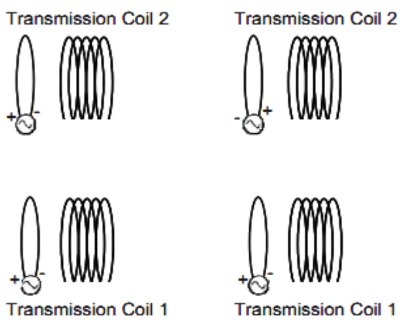
Figure 3.1.Configuration, (a) Wireless power transfer system using a transmission coil (b) Structure of coil.

3.3 Improvement of the transfer efficiency of the proposed system

In general, the transfer efficiency of a large coil is higher than that of a small coil for the same distance of d. In the following part of this paper, distance d is normalized by the diameter of the coil. A normalized distance dn is defined as dn=d/r1 and a normalized distance dtn is defined as dtn=dt/r1.

3.4 Measurement results

S-parameters are measured by a vector network analyzer. S21 between the input port of the transmission circuit and the reception loop is measured and evaluated as the transfer efficiency. In this work, a power divider circuit is used in a transmission circuit just for the purpose of the evaluation of the proposed system. The first mode and the second mode are realized by the opposite excitation of the loop for Transmission Coil 2 as shown in Fig. 2. Fig. 3 shows a photograph of the measurement system. Fig. 4 shows the measurement results of the transfer efficiency when the orientation angle T is from 0 degree to 90 degrees



(a)The first mode (b) The second mode (In
phase (Out phase excitation) excitation)

Figure: 3. 2. Transmission mode, (a) First mode, (b) Second mode.

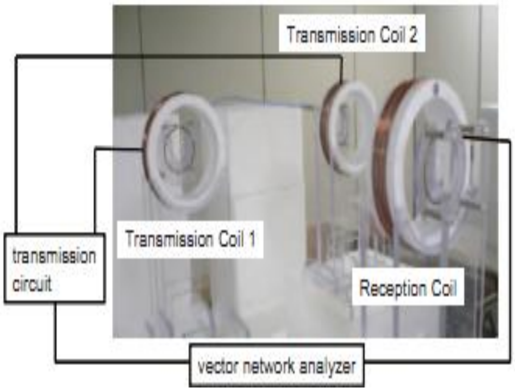


Figure: 3.3. Photograph of the measurement system

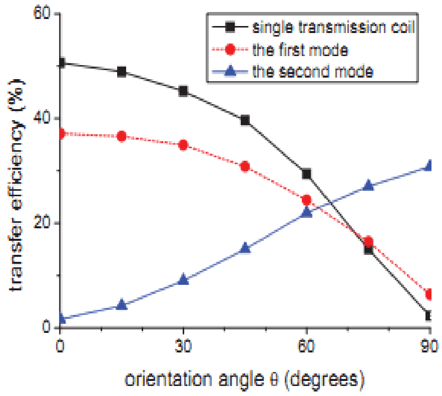


Figure: 3. 4. Measured transfer efficiency.

The transfer efficiency of a single transmission coil, which is located at the center between Transmission Coil 1 and Transmission coil 2, is also measured for comparison. As for comparison test for the single transmission coil, the transmission circuit is replaced to a through. The normalized distance dn is 2.67 and the normalized distance dtn is 2.67. The maximum transfer efficiency which is obtained around 27 MHz is plotted in Fig.3. 4.

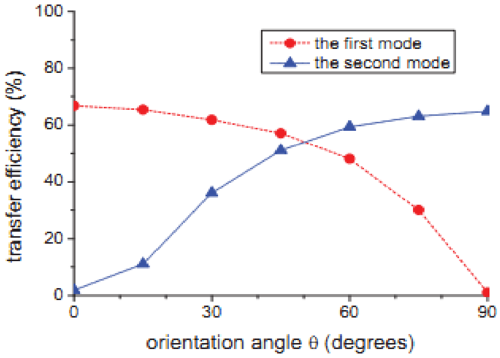


Figure: 3.5. Calculated transfer efficiency.

The maximum transfer efficiency for the single transmission coil is obtained when the orientation angle □ ofthe reception coil is 0 degree.

On the other hand, the transfer efficiency for the single transmission coil becomes minimal when the orientation angle □ equals 90 degrees. In some applications where the orientation of the reception coil is difficult to keep fixed, an appropriate countermeasure against the decline of the transfer efficiency is desired. The transfer efficiency of the first mode is just a little lower over most orientation angles than that for the conventional single transmission coil and has a similar trend according to the orientation angle. On the other hand, the curve of the transfer efficiency for the second mode has a quite different trend from the curve for the conventional single transmission coil. The maximum transfer efficiency for the second mode is obtained when the orientation angle □ equals 90 degrees. The transfer efficiency for the second mode becomes minimal when the orientation angle □ is 0 degree. In the proposed system, when the orientation angle □ is less than 60 degrees, the first mode is a suitable mode. On the other hand, when the orientation angle □ is greater than 60 degrees, the second mode should be chosen. The transfer efficiency of the proposed system is higher than that of the conventional single transmission coil when the orientation angle □ is greater than 70 degrees.

3.5 Calculation results

The transfer efficiency of the proposed wireless power transfer system using a transmission coil array is calculated by a method of moment [5]. The coils and the loops are modeled in the simulation, while the transmission circuit is out of scope of the simulation. Fig. 5 shows the simulation results of the transfer efficiency for the first mode and the second mode. The maximum transfer efficiency for the first mode is obtained when the orientation angle □ is 0 degree. On the other hand, the maximum transfer efficiency for the second mode is obtained when the orientation angle is 90 degrees. The simulation results also confirm the effect of the proposed system. Table: 1. S-parameters of the power divider

S-parameters	(dB)
S_{aa}	-9.6
S_{bb}	-10.2
S_{cc}	-10.3
S_{ba}=S_{ab}	-3.7
S_{ca}=S_{ac}	-3.7
S_{cb}=S_{bc}	-4.2

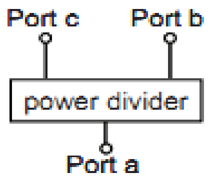


Figure: 3.6. Definition of the port of the power divider.

3.6 Mutual coupling between two transmission coils

The comparison between the measurement and the simulation shows that the measured transfer efficiency is lower than the simulation result. In the simulation, the transmission circuit is not modeled. A loss caused by the transmission circuit is discussed below. Table1 shows the S-parameters of the power divider. Fig. 6 is the definition of the port of the power divider. Sba and Sca are -3.7 dB. The ideal value of the Sba and Sca is -3 dB. The characteristics of the Sba and Sca of the power divider affect the transfer efficiency. Additional concern is that the mutual coupling between Transmission Coils 1 and 2 by means of their geometric mutual positions, which does not include the coupling through the power divider, might cause the power transmission between these transmission coils and reduce the efficiency of power transfer to the reception coil. Because the coupling Sba through the power divider between Ports b and c is -4.2 dB according to our measurement, the power which is fed to partner transmission coil would be suffered substantial additional loss even though some part of the back-fed power is re-transmitted by the original transmission coil.

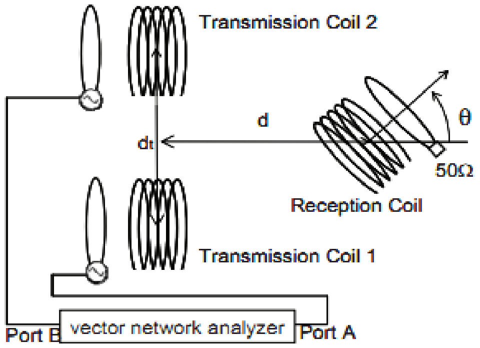


Figure: 3. 7. Measurement setup for the mutual coupling.

Fig: 3.7 shows the setup for the measurement of the coupling SBA between Ports A and B, which is caused by the said mutual coupling between the transmission coils. The reception loop is terminated by 50 ohms load.

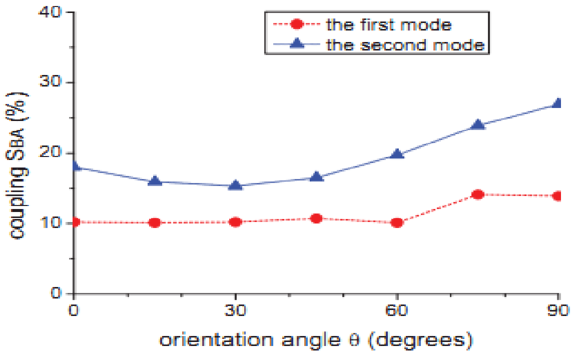


Figure: 3. 8.Measured coupling SBA.

Fig: 3.8 show the measured coupling between the transmission coils for each mode. Note that the coupling has a dependency on the orientation of the reception coil and the transmission modes. The coupling for the second mode is higher than that for the first mode. The substantial coupling is observed and thus might by one of major reasons for the difference between measurement and simulation. In particular, the transfer efficiency of the second mode is could be decreased by the mutual coupling between the transmission coils. The difference between the measurement results and the simulation in the second mode is caused by the characteristics of the power divider and the mutual coupling between the transmission coils.

3.7 Summary:

We have reviewed the possibility of wireless power transfer by using via magnetic resonance transmission coil in a theoretical and analytical way, and we find that it is possible to transfer energy. The effect of the system was confirmed by the measurement and the simulation. The system has two modes for phase excitation alternation. The decline of the transfer efficiency was improved by using the suitable modes. One of the reasons for the difference between the measurement results and the simulation results was suggested to be the mutual coupling between the transmission coils. In this paper, the first mode (in-phase excitation) and the second mode (out-of-phase excitation) were realized by the orientation of the loop for Transmission Coil 2. Also, good impedance matching was obtained by adjusting the gaps between each coil and the loop. Development of the other and practical means for the excitation mode control as well as impedance matching besides the gap adjustment in this study is subject to the future work.

IV. Resonance Based Wireless Power Transmission by Using Strongly Coupled Magnetic

4.1 Introduction:

This method is applicable for the autonomous electronics devices such as laptop, cell phones, robots, PDAs etc.

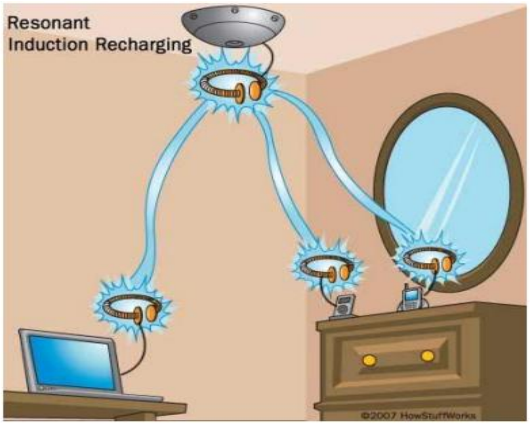


Fig: 4.1: Shows Resonance Frequencies to Multiple Sources

The problem with these devices is that despite their portability and ability to communicate wirelessly, these devices still require regular charging, usually by plugging into a wall outlet. The ability to provide power for these and other electric devices wirelessly would greatly increase their portability and accessibility for the public Previous schemes for wireless power transmission included attempts by the late scientist Nikola Tesla [6], [7] who demonstrated wireless power transfer using large copper elements in the early 1900s.Nikola Tesla devoted much effort to developing a system for transferring large amount of power over considerable distance. His main goal was to bypass the electrical-wire grid, but for a number of financial and technical difficulties, this project was never completed. His invention, however, required large scale construction of 200 ft tall masts. It also produced undesirably, and sometimes dangerously, high voltages that approached 100,000,000 V [8]. Later attempts at wireless power led to the development of microwave power transmission [9], [10] but its line-of-sight requirements meant that any practical power source needed to be high in the sky. Previous proposed projects included large power platforms as well as microwave-beaming satellites [11], [12] .Both Tesla's devices and the later microwave power were forms of radiative power transfer. Radiative transfer[13],which is used in wireless communication, is not particularly suitable for power transmission due to its low efficiency and radiative loss due to its omni directional nature (since the power captured is proportional to cross-section of receiving antenna, and most of power is radiated in other directions). More recently, a company by the name of Splash power [14] developed magnetic charging pads on which to place electronic devices.

The pad used magnetic induction to transfer energy to a specially designed receptor on the electronic device being charged. This device required contact between the pad and electric device, as well as a specialized addition on the electronic devices needing to be charged. This made implementation impractical on a large scale. Earlier attempts such as Tesla's inventions[6],[7]microwave transmission and the magnetic charging pads represented long range and close range wireless power transmission – however, implementation of those inventions has been slow or nonexistent, due to impracticalities in their design. An alternative approach which was pursued by MIT team [15] is to exploit some near field interaction between the source and device, and somehow tune this system so that efficient power transfer is possible. A recent theoretical paper[15] presented a detailed analysis of the feasibility of using resonant objects coupled through the 'tails' of their non radiative fields for midrange energy transfer. Intuitively, two resonant objects of the same resonant frequency tend to exchange energy efficiently, while dissipating relatively little energy in extraneous off resonant objects. In systems of coupled resonance (e.g. acoustic, electromagnetic, magnetic, nuclear), there is often a general "strongly coupled" regime of operation [16]. If one can operate in that regime in a given system, the energy transfer is expected to be very efficient. Midrange power transfer implemented in this way can be nearly omni directional and efficient, irrespective of the geometry of the surrounding space, with low interference and losses into environmental objects. The above considerations apply irrespective of the physical nature of the resonance. Here, we focus on one particular physical embodiment: magnetic resonance [18].In case of Magnetic resonance interaction between the object occurs predominantly through the magnetic field they generates. Magnetic resonances are particularly suitable for everyday application [19] because most of the common materials do not interact with magnetic fields, so interactions with environmental objects are suppressed even further. Operating on resonance is necessary condition for such system, but not sufficient to achieve good efficiency at mid range distances. Operation in strong coupling regime, for which resonance is precondition, is what makes the power transfer efficient. Another experimental paper [20] presented a simulation of back electromotive force (back-EMF) in the receiving coil related with different transfer distance and with driving frequent

4.2 Theory of strongly coupled systems

In order to achieve Efficient Power transfer there are some ways used for tuning parameter of given system so that it is operated in strongly coupled rejoin. Coupled Mode Theory (CMT)[21],[22] provides a simple and accurate way of modeling the system and gives a more understanding of what makes power transfer efficient in a strongly coupled rejoin. CMT said that when two resonators have equal frequencies then, when resonator 1 is excited at t=0 and a1=1 and resonator 2 is unexcited i.e. a2 = 0 then phases of two solutions evolve at different rate, and after time t= π/2k all of excitation will be transferred to other resonator. For CMT the needful condition is that k<<ω1, 2.Here ω1,2 are individual Eigen frequencies.CMT gives following set of differential equation by analyzing system as;

am(t) = ─ (iwm─Γm).am(t) ─ Σ iknm .an(t) + Fm(t)

The first assumption of coupled mode theory is that range of frequencies of interest is sufficiently narrow that the parameter in above equation can be treated as constants and coupled differential equation can be treated as linear. The second is overall field profile can be described as superposition of modes due to each objects. This condition implies that interaction between resonators must not be strong enough so as to significantly distort the individual Eigen modes. A numerical solution of above coupled magnetic resonance equation is also given [23].The basic principle behind this system is that, if two resonant circuits tuned at same frequency then their near fields (consisting of evanescent waves coupled by means of evanescent wave coupling) then due to this evanescent wave coupling standing wave developed between inductors, which can allow energy to transfer from one object to other within time. Evanescent wave coupling is a process by which electromagnetic waves are transmitted from one medium to other by means of evanescent exponentially decaying electromagnetic field. Electromagnetic evanescent waves have been used to exert optical radiation pressure on small particle in order to tap them. The reason behind use of non-radiative transfer scheme for this system is, in case of non-radiative objects when energy is applied then it remains bound to them, rather than escaping to space. Here in this case ‘tails’ of energy, which can be many meter long flicker over surfaces. If you bring another resonant object with same frequency close enough to this ‘tails’ then energy can tunnel from one to other object. The diagram which shows two objects, one is denoted by Source (S) and Device (D) is as shown in figure.1 [19]. The coupling coefficient [17] kSD and kDS are dependent on each other. We use k = kDS = kDS, here k is related to transfer of energy between two oscillator.

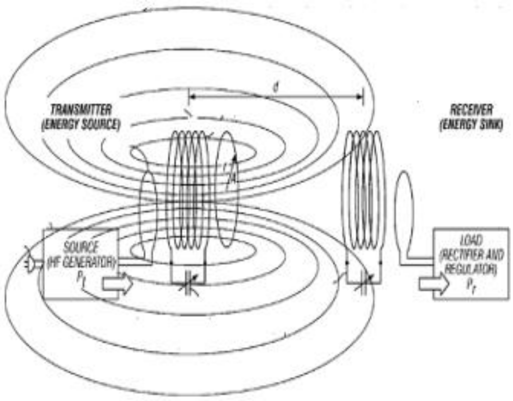


Figure: 4.2.Block diagram of magnetic wave based wireless power transmission system.

The Q factor which is used to determine the rate at which energy loses for above system is;

In one period of oscillation the resonant object loses 1/Q of its energy. Once device is excited by source which in turn driven at constant frequency, we can extract energy and convert it in to useful work by adding a load (denoted by subscript w).More generally the load has effect of contributing an additional term with unloaded device’s object decay rate(ΓD) . Thus total decay rate at device is,

ΓD ' =Γ D + ΓW.

In case of efficiency of system for efficient energy transfer above system can be design such that the rate of energy transfer between source and device is greater than rate of energy dissipation that is, k>>(√ΓS × √ΓD),where (√ΓS × √ΓD) is rate at which source and device dissipating energy. If above condition is satisfied then energy travels from source to device before too much get wasted.

4.3 Analytical Model of Self Resonating Coil

The experimental realization [15],[17] of power transfer scheme done by MIT team consist of 2 identical self resonating coils made up of an electrically conducting wires of total length ‘l’ and crossectional radius of ‘a’ wound in to helix of ‘n’ turns, having radius ‘r’ and height ‘h’. We can define effective inductance ‘L’ and effective capacitance ‘C’ for each coil is,

$$L = \frac{\mu_0}{4\Pi|I_0|^2} \iint dr\, dr' \frac{J(r) . J(r')}{|r - r'|}$$

$$\frac{1}{C} = \frac{1}{4\Pi\varepsilon_0|Q_0|^2} \iint dr\, dr' \frac{\rho(r) . \rho(r')}{|r - r'|}$$

Here J(r) is spatial current density and ρ(r) is spatial charge density and Io is current flowing through coil at initial condition and Q0 is total charge at I = 0. The energy contained in coil is given as,

$$U = \frac{1}{2} L |I_o|^2 = \frac{1}{2C} |Q_o|^2$$

In this model the coil dissipating energy through two mechanisms, one is Ohmic (Resistive) loss and other is Radiation loss [15], [17].Given this relation and equation of continuity the resulting resonance frequency is,

$$f_0 = \frac{1}{2\Pi\sqrt{LC}}$$

The efficiency of power transfer depends only on 'Γ', the intrinsic decay rate of magnetic transfer (due to radiated losses and absorption by other objects), and 'κ', the coupling coefficient that describes the strength of resonance between the two resonating coils. Both κ and Γ are functions of distance between resonating objects and resonance frequency.

The parameters κ for the transfer path and Γ for the two coils were experimentally adjusted to achieve strong coupling. The experimental power transfer efficiency of the coupled coils decayed with distance, as expected from the theory. The power transferred from source to device coil is given as,

$$P_{DS} = \Gamma \, L |I_{S,D}|^2 = -iwMI_S I_D \, .$$

where M is effective mutual inductance.

4.4 Implementation of System and Results

Two identical helical copper coils, one for the source and one for load, were constructed by the MIT team [15] for magnetic coupling. By fine tuning the height of coils, they were able to cause strong magnetic resonance coupling between two coils at a midrange distance. The source coil was in turn inductively coupled to a single copper wire loop which is attached to Colpitts oscillator.

The receiving magnetic coil was inductively coupled to a copper wire loop attached to a 60 W bulb. To test the accuracy of their theoretical derivations, MIT team compares theoretical and experimental values. In Fig.4.3. [19] Experimental and theoretical values of efficiency with distance are compared.

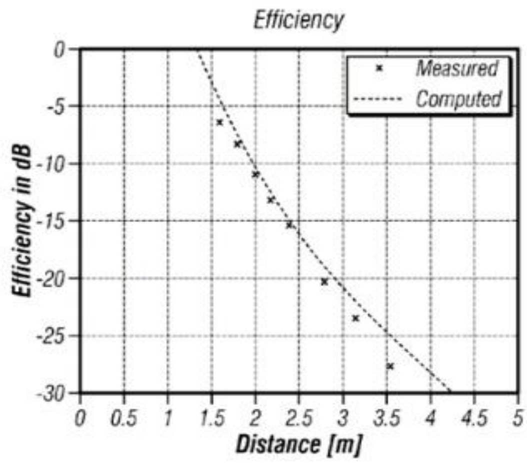


Fig: 4.3. Transfer Efficiency over Distance

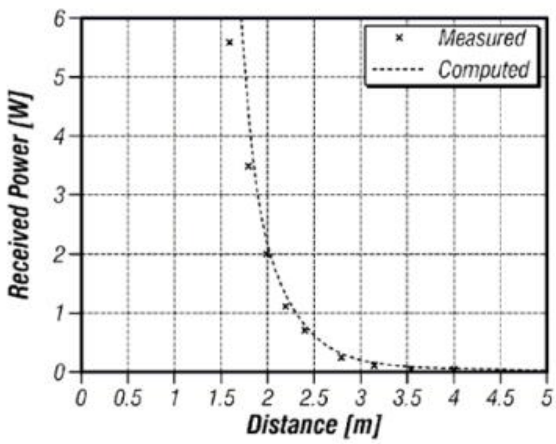


Fig: 4.4. Received Power over Distance.

In Fig.4.4.experimental and theoretical values of received power with distance are compared [19].Whereas in Fig.4.5 and Fig.4.6.experimental and theoretical values of coupling coefficient over distance and ratio of k/Γ over distance are compared respectively [15]

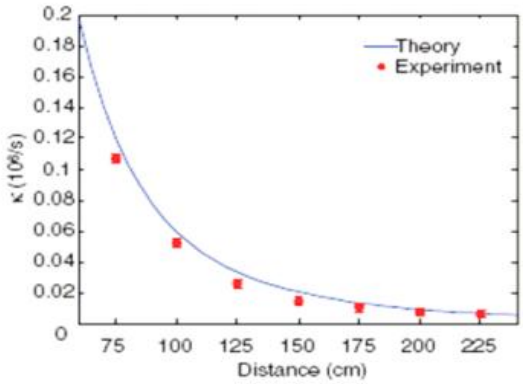


Fig.4.5. Coupling Coefficient over Distance

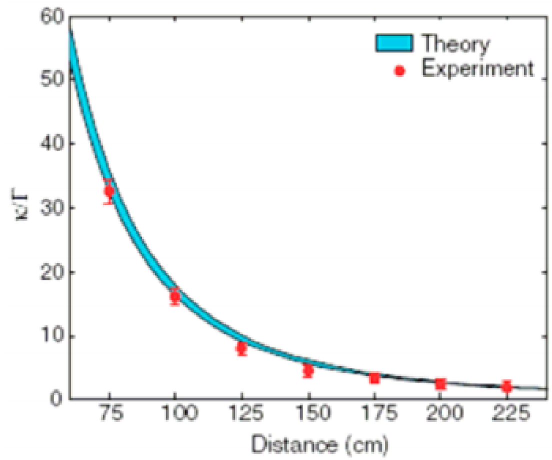


Fig: 4.6. Ratio of k/Γ over Distance.

4.5 Summary

After reviewing the possibility of wireless power transfer by using strongly coupled magnetic resonance in a theoretical and analytical way, and we find that it is possible to transfer energy over distance up to 8 times the radius of coils with nearly 40% efficiency. We also find that efficiency, received power and coupling coefficient are decreases with increase in distance between two resonators.

V. Wireless Solar Energy: A Magnetic Resonance Approach

5.1 Introduction

In recent years, there has been an increasing trend of using renewable energy, including installing solar panels in residential homes, propelled by public concerns about the environment. Currently, the cost of solar panels has decreased substantially.

Considerable structural modification and installation, including the creation of a through hole, are required for connecting a cable to the house interior and properly grounding the panel to prevent danger from lightning strikes. The associated cost is high, often comparable to the purchase cost of the panel or even higher. The Department of Electrical & Computer Engineering, University of Pittsburgh describes a novel method for wireless transmission of solar power to the interiors of homes and buildings. This method is based on wireless electricity (witricity), a new technology developed recently in the field of physics. Two thin film witricity resonators are placed behind the solar panel and on the inside of the building, with no cable connection between the two. High-efficiency energy transfer is achieved across a wall or roof in the form of magnetic resonance at approximately 7 MHz Significant savings in installation cost can potentially be achieved using this wireless energy transfer method, encouraging adoption of a "green" source of energy. They have presented a method to transmit energy from solar panels through structural walls or roofs using a newly developed wireless energy transfer technology called witricity. A comparison between existing solar installations and the proposed wireless method is shown in Fig. 1. Their system utilizes magnetic fields below 10 MHz which are essentially unaffected by commonly used home construction material. Because of the wireless connection, most structural modifications to the house can be eliminated, installation costs can be reduced, and solar panels can be moved or replaced easily. Since magnetic fields have less biological effects on the human body than electromagnetic fields at higher frequencies, the witricity approach is safer than a traditional radio-frequency approach at comparable power levels.

In this work, they have made the initial attempt to use wireless energy transfer for solar panels. The primary goal of this work is to demonstrate that this energy transfer is technically feasible. Therefore, they focus only on the applicable theory and the witricity resonator part of the system.

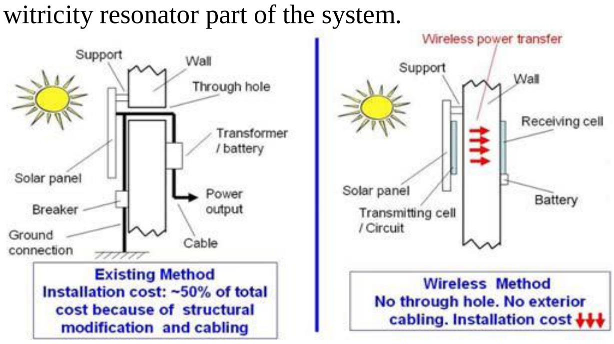


Fig: 5.1. Comparison of existing and wireless solar panel systems.

5.2 Witricity Theory

Witricity is a recent development in physics that allows efficient energy transfer over a distance without wires. Unlike traditional methods using electromagnetic waves radiated throughout the entire surrounding space, witricity transfers power along a virtual path between the source and the target which resonate at the same frequency. Off-resonant objects in the surrounding area interact only weakly with the resonant system. As a result, the efficiency of energy transfer is much higher. Researchers at MIT transferred 60W of power over seven feet with 40% efficiency. A different design by Intel recently reached 75% efficiency over three feet. Witricity systems can be designed to use different types of fields. In their particular application the magnetic field is utilized. Their system consists of four components: two high-Q resonators (a source resonator and a device resonator) which exchange energy back and forth, a driving loop which is powered externally, and an output coil which captures energy for the load (Fig. 5.2). Energy is added to the resonant system via magnetic coupling between the driving loop and the source resonator, and lost from the system via inherent component losses, radiated energy, and power dissipation in the load.

Fig: 5.2. General witricity system design.

The energy in the witricity system can be modeled with a pair of differential equations by using coupled mode theory:

$$\frac{da_1(t)}{dt}=(j\omega_1-\Gamma_1)a_1(t)+j\kappa a_2(t)+f(t)$$

………5.1

$$\frac{da_2(t)}{dt}=(j\omega_2-\Gamma_2)a_2(t)+j\kappa a_1(t)$$

………5.2

ai(t) is defined such that |ai(t)|2 is the energy over time in resonator i. ωi and Γi are the resonant frequency and loss factor, respectively, associated with resonator i, κ is the coupling factor between resonators, j is the imaginary number √−1 , and f(t) is the input energy from the driving loop.
To calculate ai(t), we use the Laplace transform and obtain

$$L\{a_1(t)\}=\frac{(L\{f(t)\}+a_1(0))(s-j\omega_2+\Gamma_2)+j\kappa a_2(0)}{(s-j\omega_1+\Gamma_1)(s-j\omega_2+\Gamma_2)+\kappa^2}$$

…….5.3

$$L\{a_2(t)\}=\frac{j\kappa(L\{f(t)\}+a_1(0))+(s-j\omega_1+\Gamma_1)a_2(0)}{(s-j\omega_1+\Gamma_1)(s-j\omega_2+\Gamma_2)+\kappa^2}\,.$$

……5.4

Let us examine how the energy in the system changes over time. Assume f(t) = 0 (no input energy) and, at arbitrary t = 0, the total energy, A, is in resonator 1 and no energy is in resonator 2, i.e. a1(0) = √A and a2(0) = 0. This gives

$$L\{a_1(t)\}=\frac{(s-j\omega_2+\Gamma_2)\sqrt{A}}{(s-j\omega_1+\Gamma_1)(s-j\omega_2+\Gamma_2)+\kappa^2}$$

…………5.5

$$L\{a_2(t)\}=\frac{j\kappa\sqrt{A}}{(s-j\omega_1+\Gamma_1)(s-j\omega_2+\Gamma_2)+\kappa^2}$$

………5.6

from which they compute the time domain solutions

$$a_1(t)=\sqrt{A}e^{-\frac{(\Gamma_1+\Gamma_2)}{2}t}e^{j\frac{(\omega_1+\omega_2)}{2}t}\left[\cos\left(\frac{t}{2}\sqrt{((\omega_1-\omega_2)-j(\Gamma_2-\Gamma_1))^2+4\kappa^2}\right)+\frac{(\Gamma_2-\Gamma_1)-j(\omega_1-\omega_2)}{\sqrt{((\omega_1-\omega_2)-j(\Gamma_2-\Gamma_1))^2+4\kappa^2}}\sin\left(\frac{t}{2}\sqrt{((\omega_1-\omega_2)-j(\Gamma_2-\Gamma_1))^2+4\kappa^2}\right)\right]$$

………..5.7

$$a_2(t)=\sqrt{A}e^{-\frac{(\Gamma_1+\Gamma_2)}{2}t}e^{j\frac{(\omega_1+\omega_2)}{2}t}\left[\frac{j2\kappa}{\sqrt{((\omega_1-\omega_2)-j(\Gamma_2-\Gamma_1))^2+4\kappa^2}}\times\sin\left(\frac{t}{2}\sqrt{((\omega_1-\omega_2)-j(\Gamma_2-\Gamma_1))^2+4\kappa^2}\right)\right]$$

……5.8

Equations (5.7) and (5.8), being very general, are overly complex for our application. Practically, resonators in a witricity system are designed with minimal difference between their resonant frequencies. Also, if the resonators are identical in structure and we neglect the effect of the load in our examination, their loss factors will be equal. Thus we assume ω1 = ω2 = ω and Γ1 = Γ2 = Γ and simplify (5.7) and (5.8) to the following:

$$a_1(t)=\sqrt{A}e^{-\Gamma t}e^{j\omega t}\cos(\kappa t)$$

………..5.9

$$a_2(t)=\sqrt{A}e^{-\Gamma t}e^{j\omega t}j\sin(\kappa t)$$

……..5.10

If the ratio between the coupling and loss factors is high enough, practically κ/Γ >> 1, energy can be efficiently exchanged between resonators at a high rate. This phenomenon differs significantly from the traditional magnetic induction and radio transmission systems where the energy flow is essentially unidirectional (from the transmitter to the receiver). From (7)-(10), we can interpret that energy in a witricity system oscillates between each resonator. If we examine the total system energy is

$$E_T=E_1+E_2=|a_1(t)|^2+|a_2(t)|^2=Ae^{-(\Gamma_1+\Gamma_2)t}$$

…………5.11

We see that it decays exponentially according to the loss rates. As a result, energy can efficiently be kept in a low-loss resonant system until output to a load via magnetic coupling.

Input energy from the driving loop, f (t), must simply be enough to compensate the system and load losses in order to sustain the resonant oscillations. Additionally, both the literature and our own experiments have indicated that the source and device resonators do not have to be in precise alignment, which facilitates the use of witricity in many applications.

5.3 Method: Planar Coil Design

Because of the importance of the resonator parameters, they give much consideration to the design of the coils for the witricity system. The resonator design described in is an unconnected large coil having a shape unfavorable for the solar application. Here we present a thin-film design for both the source and device resonators, suitable for use with a solar panel and flat receiving device. Their design consists of two patterned layers of 0.066 mm copper foil tape conductor on either side of one layer of 0.255 mm clear polycarbonate film used as a resonator base and insulator. As illustrated in Fig. 5.3(a), the two conductor layers provide a coil and several local capacitors across the insulator layer, forming a complex LC oscillator. The resonant frequencies of the resonators are tuned by adjusting the length of the coils and the number and lengths of the capacitive strips on the coils as well. Theirs are tuned to 6.54 MHz, close to one of the official industrial, scientific, and medical (ISM) frequencies (6.78 MHz). Fig. 5.3(b) shows one of the coils after completion with a side length of 32 cm. This fits the shorter dimension of a 10-Watt solar panel, roughly 35 cm. A driving loop was constructed from insulated 12-gauge copper wire. The output coil was built in a spiral fashion from ¼-inch copper pipe, seen in Fig.5. 4(c).

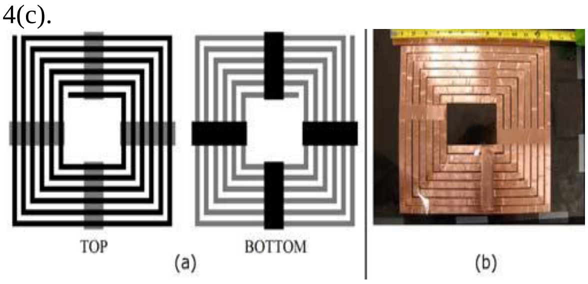


Fig: 5.3 (a) Resonant coil structure. The thin polycarbonate substrate (not shown) lies between the copper foil layers, the closest copper layer being darker in color. (b) “Bottom” view of actual constructed resonator.

5.4 Experimental Setup

The wireless transfer system was set up as shown in Fig. 5.4. A brick wall was erected between the source and device resonant coils. The driving loop was powered on the source coil side by an amplifier with a simulated solar panel power input and driven by a sinusoidal signal from a function generator. The load coil was positioned near the resonant device coil to draw energy from it via magnetic coupling. Because currently they cannot accurately determine the effects of this electromagnetic exposure on the human body next to the experimental device, then intentionally use very low RF power (less than one Watt) to operate the witricity system. Calculated efficiency results at higher energy levels will be the same since the system is theoretically linear.

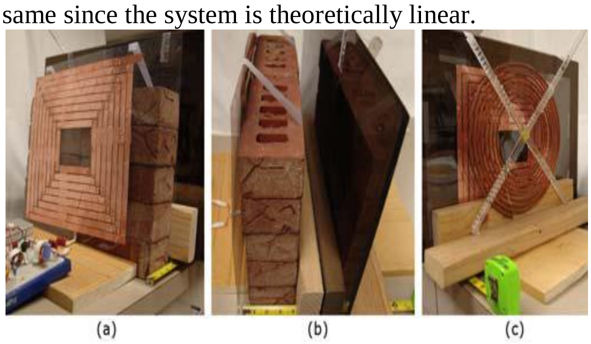


Fig: 5.4. (a) Transmitting side of the system with amplifier and resonant coil. (b) Constructed wall between resonant coils. (c) Receiving side of the system, showing the square resonant coil and spiral load coil.

5.5 Power Transfer Efficiency

The power transfer efficiency of the setup is calculated by dividing the power received on the load coil side, PL, with the power transmitted at the driving loop, PT. The load resistance was chosen to maximize power transfer to the load, a 1.8kΩ resistor for these experiments. The sinusoidal voltage amplitude, VL, across this resistor, RL, is measured to calculate the received power in the load by the equation PL = VL 2/ (2RL). On the transmitting side, PT is measured as the power going to the driving loop. Fig. 5(a) illustrates the setup used in this measurement. A resistor R (56Ω in this case) is put in series with the driving loop. The voltage VR is measured across R in order to determine the amplitude of the sinusoidal current going into the driving loop (IR = VR/R). The voltage across the driving loop, VC, and the total voltage across both the resistor and driving loop, VT, is also measured in order to calculate the phase, γ, between the voltage and current of the driving loop, using the law of cosines (see Fig. 5(b)). The total power going to the driving loop is calculated as PT = VC*IR*cos (γ)/2.

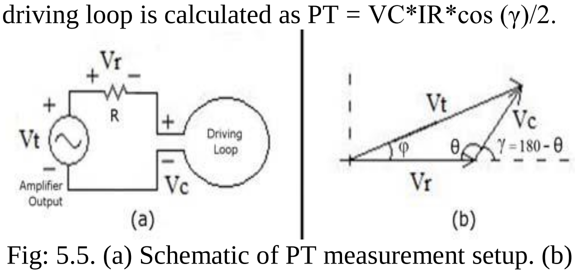


Fig: 5.5. (a) Schematic of PT measurement setup. (b) Voltage relationships to calculate the phase angle between the driving loop’s voltage and current.

5.6 Experimental Results

Fig. 6 shows the measured power transfer efficiency of the witricity system at various distances. As can be seen, the efficiency decreases as a function of resonant coil separation, with the highest efficiency being 52% at the smallest distance (5.75 inches), and decreasing to 4% at a distance of fourteen inches. With most exterior walls ranging in thickness from four to nine inches, this first generation witricity system would provide for an energy transfer efficiency of ~30% to more than 52% in the solar panel application. The energy transfer performance was essentially unchanged when other objects such as plastics, plasters, water, and even a small number of metal screws and nails, were placed between the two resonators. Perfect alignment of the resonators is also not required to maintain efficiency, as opposed to standard inductive coupling in which alignment is an essential requirement.

Fig: 5.6. Power transfer efficiency is measured as the ratio of power delivered to the load to the power delivered to the driving loop, PL/PT. The highest efficiency for this system is 51.9% at 5.75 in.; the lowest is 4.0% at 14 in.

In practice, it is favorable to use the backside of the solar panel as the base of the source resonant coil. They performed an additional experiment in which the coil was attached directly to the back of a solar panel. The panel consists of a plastic substrate material with photovoltaic cells on one side. The cells are connected with a network of metal strips to collect current from individual cells. They again used a power supply to simulate the solar panel due to the lack of indoor sun. Although they utilized exactly the same setup as that in the previous experiment, except for the presence of the solar panel, they observed a significant reduction in energy transfer efficiency. The highest measured efficiency at the closest possible distance (5.75 inches for this setup) was 33%. Although the efficiency suffered, of note is the interesting fact that the actual transmitted power, PT, decreased tremendously, to a quarter of that without the solar panel present.

5.7 Summary

A wireless energy transfer system based on witricity technology has been proposed to reduce the cost of solar panel installation and encourage its adoption. Experiments on an initial system utilizing appropriate flat thin-film resonators display power transfer efficiencies higher than fifty percent. Future research promises to increase to establish witricity as a cost-efficient solar installation solution.

VI. Wireless Power by Solar

6.1 Introduction

Solar power is the conversion of sunlight into electricity, either directly using Photovoltaic's (PV), or indirectly using concentrated solar power (CSP). Photovoltaic's convert light into electric current using the effect. Concentrated solar power systems use lenses or mirrors and tracking systems to focus a large area of sunlight into a small beam.

Figure: 6.1.Solar Panel.

6.2 PHOTOVOLTAICS

A solar cell, or photovoltaic cell (PV), is a device that converts light into electric current using the effect. Photovoltaic technology involves the direct conversion of sunlight into electricity through the use of photovoltaic (PV) modules. Solar cells (or photovoltaic cells) are composed mainly of silicon (Si).Under certain conditions electrons from silicon atoms can be released and become available to move as part of an electric current.

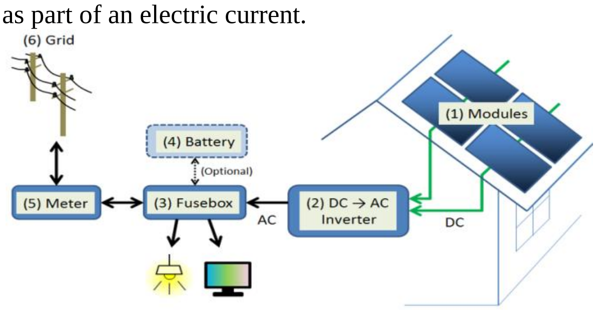


Figure: 6.2.PV- System.

When solar cells are joined physically and electrically and placed into a frame they form a solar Panel or PV module (Figure 3). Panels joined together form a solar array. A typical module of 1 m2 would be able to produce around 100W. Commercial PV systems are about 7% to 17% efficient.

6.3 EQUIPMENTS:

The basic equipments of solar panels are given below.

BATTERY STORAGE

Off-grid PV systems have traditionally used rechargeable batteries to store excess electricity. With grid-tied systems, excess electricity can be sent to the transmission grid. Net metering programs give these systems a credit for the electricity they deliver to the grid. This credit offsets electricity provided from the grid when the system cannot meet demand, effectively using the grid as a storage mechanism. Credits are normally rolled over month to month and any remaining surplus settled annually. The battery storage (bank) is used to store electricity. It enables the continuity of power to the load in the event of power failure or for solar sites in the event of cloudy weather and at night. Both nickel cadmium and sealed – lead acid batteries are used for remote area power supply systems.

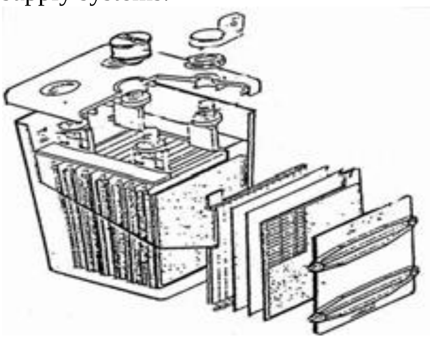


Figure: 6.3.Constructional Features of a Lead Acid Battery.

The cyclic energy efficiency of a battery (usually 80% for a new lead-acid battery operated in the optimum region) is also paramount, since energy lost requires a larger input source to replace it. Other important factors that determine life-cycle costs (apart from capital cost) are: the number of cycles delivered (at a certain depth of discharge – DOD), lifetime (usually 3 to 7 years in well-designed systems), and how often it must be maintained.

Types of Batteries

Lead Acid Battery

The lead acid battery (Figure 5) has a stable voltage (2.0 V per cell) and a stable power output.

The cost is also low compared with other batteries. Its weaknesses are low energy density (Important in vehicle applications), the need for regular maintenance, and the decrease in battery performance and life in deep discharge use (80 per cent depth of discharge). The Life Cycle Cost can be high, especially in the case of batteries subject to frequent discharge.

Sealed Lead Acid Battery

The sealed lead acid battery uses the same principles as the lead-acid battery but the battery is sealed in leak-proof case. Sealed batteries need to be carefully monitored to prevent overcharging and electrolyte loss through their safety vents. These batteries can be transported safely without fear of acid spillage.

Nickel Cadmium

Nickel Cadmium batteries are still more expensive, but have the advantage that they do not suffer from being operated at a low state of charge, as do lead-acid batteries. Nickel cadmium cells are resilient to both overcharge and undercharge and may even be recovered if they go into polarity reversal. They may be used in a wide temperature range, from – 40 to +140 ºC.

Battery Capacity

The energy stored in batteries is measured in ampere hours (Ah). Every cell when fully charged has the potential for producing a certain number of Ah. The capacity of the battery is specified by manufacturers in Ah under a certain discharge rate and cell temperature. If energy stored in a battery is C25=100 Ah then it can provide a current of 4 Amps for 25 hours. Energy in Kilowatt
Hours (kWh) = Ah x V / 1000, in which V is the battery voltage.

Charging Rate

Charging rates are specified by battery manufacturers and depend on the battery capacity and state of charge.

Depth of Discharge

This is a measure of how much of the total battery capacity has been consumed and is usually given in percent. The maximum recommended depth of discharge is usually around 70% (refer to the battery manufacturer's specifications). Figure 6 illustrates Battery Cycle Life Vs Depth of Discharge

State of Charge

This is a measure of how much of the initial battery capacity is available and is expressed in terms of % of rated capacity. For example a battery, which is at 30% depth of discharge, would be at 70% state of charge.

Battery Voltage

Battery voltage is measured in Volts (V). The operating voltage (12 V / 24 V / 48V) of the battery cell is not constant due to factors such as the internal resistance of the cells and the temperature.

Maintenance of Batteries

Lead acid batteries should be checked regularly for water loss. Water loss results primarily from gassing during charging. Inspection should also be done for any acid leaks, corrosion and cracks in the casing. Nickel Cadmium (NiCd) batteries do not suffer adversely from conditions of "electrical abuse" (rapid charge or discharge) that would be damaging to lead-acid batteries and are quite rugged. Small traces of sulphuric acid will ruin a nickel-cadmium battery by corroding the steel plates and cell containers. To prevent contamination, never use any tools, such as hydrometers, funnels, rubber hoses, battery fillers, etc., that have already been used for serving lead-acid batteries. Keep all vent caps closed. To prevent air from entering the cells, raise the caps only for checking the electrolyte, never for charging. Always check and service only one cell at a time.

Effect of Temperature

The rate of chemical reaction is reduced when the battery temperature is low, during cold periods. Battery capacities are usually given at a reference temperature of 25°C. At higher or lower temperatures, correction should be made using correction factor curves such as

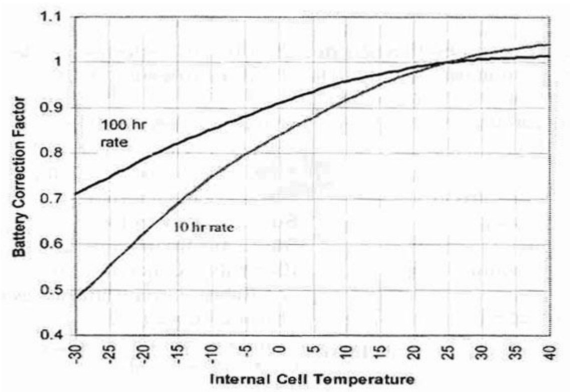


Figure: 6.4. Correction Factor as a Function of Cell Operating Temperature.ii (dependent on discharge rate). High temperatures do reduce the service life of a Ni-Cd but not as severely as lead cells.

Life Expectancy of Batteries

Batteries lose capacity over time and are considered to be at the end of their effective design life when they cannot be charged to more than 80% of their original capacity. Battery manufacturers will specify the cycle life for a particular depth of discharge. One characteristic that batteries in hybrid power systems have in common is that they are deep cycle batteries. Unlike a car battery, which is a shallow cycle battery, deep cycle batteries can discharge more of their stored energy while still maintaining long life.

Back-up generators In periods of higher loads, when the renewable energy sources are unable to meet the demand, a backup generator could be used.

Generator Control Systems

Starting a diesel engine is achieved by cranking the diesel engine either manually or electrically using a starter motor, until it "fires". To stop the diesel engine, the fuel supply must be cut off. This can be done manually or by the electrical operation of a fuel control solenoid valve.

A diesel engine may be started and stopped using one of the following methods:

-Manual start / stop;

-Key start-starter motor, battery and key switch, with manual stop;

-Local or remote manual start/stop with push buttons, starter motor, battery and fuel solenoid valve; and

-Automate start / stop – as for the manual push button type, but including full engine control and protection.

Sitting of Generators

It is important to avoid operating generating sets in locations where the exhaust gases, smoke, or fumes could reach dangerous concentrations.

Also, do not install generating sets:

-in damp situations or exposed to the weather unless suitably protected and in hazardous areas or in the same enclosure as the batteries.

When sitting, consider the noise from the generating sets. If there are residents nearby, peace and quiet is a priority, so consider the generator's noise level, listed in decibels.

-The low end of the noise range measures 50-60 decibels.

-If a generator rattles at 80 decibels, you might have to raise your voice to be heard.

Encased motors and anti-vibration devices can bring the decibels down, with a little more cost.

Consider fuel availability, handling and storage requirements.

INVERTERS

The inverter converts DC power to a regulated AC voltage and current, which is used to supply standard AC appliances.

Renewable energy sources such as PV modules and wind turbines produce DC, batteries store DC power. However, the load often requires the use of AC. To convert the DC power from the batteries to AC power an inverter is used.

There are two separate criteria for identifying inverters:

-How the DC is converted to AC; and

-Output Waveform.

How the DC is converted to AC

Rotary Inverter

A DC motor driving a 240-V generator was commonly used before the advent of solid state inverters. This is still a reliable method sometimes used in remote places. The overall efficiency is low; however a perfect sinusoidal voltage is operated.

The Basic Solid State Inverter

To produce 240 volts AC from (extra-low voltage) DC power there are two distinct steps. The voltage must be increased and the output oscillated at 50 Hertz. For years all inverters first converted the DC to 50 Hertz AC then passed the power through a transformer.

Switch Mode Inverters

A more recent development with solid state inverters has been to increase the voltage first in a high frequency switch mode converter and then turn into an AC sine wave form.

These inverters are small in size. The small surface area of high frequency converters must become substantially hotter in order to remove the same quantity of heat compared with a similarly rated low-frequency unit. The shortcoming can be partially overcome by an overall increase in size of the inverter, but there is still a problem with short-term overloads, which can rapidly overheat the high-frequency converters due to their lack of thermal mass. One advantage of these types of inverters is that they are totally silent in the human hearing range although they do emit ultrasound.

Output Waveform

Square Wave Inverters

The simplest form of square wave (Figure 8) inverter ignores the significance of the relationship between peak and various averages and provides a square wave with full pulse width. Peak and average values are both nominally 240 volts. Resistive loads and most power tools function adequately on these inverters. These inverters often have limited output voltage regulation and the voltage varies widely with changes in the input voltage and load. Some type exceeds 300 volts without a substantial load. This can severely damage sensitive equipment.

Stepped Square Wave

Most square wave inverters attempt to emulate the performance of a sine wave generator to some extent. Using narrow pulses allows the peak voltage to be raised to close to that of a true sine wave. This gives an output more similar to a sine wave and carries much less energy as harmonic currents. However the peak voltage cannot be kept stable and varies in direct proportion to the input voltage. These inverters are usually known as “modified square waves” (Figure 9), “quasi sine wave”, and “modified sine wave”.

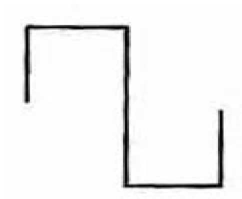


Figure: 6.5.Squarewave

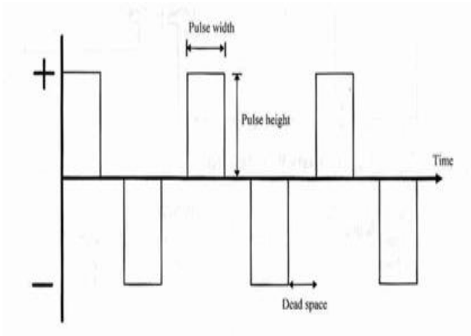


Figure: 6.6. Modified Square Wave

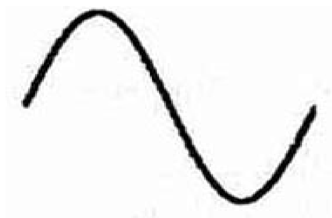


Figure: 6.7. Sine Wave

Sine Wave Inverter

Some appliances will only function correctly when supplied with a low-distortion sine wave. The wave in these “synthesized” sine wave inverters are built up from short pulses (Figure 10).

Bi-directional Inverters

With appropriate programming of the microprocessor, and appropriate semi conductors the inverter may also be operated as a high-efficiency battery charger. An extension of this versatility is the interactive inverter, which can synchronize with an external source and supply additional capacity to a generator or weak power transmission line.

6.4 Protection Circuits

Overload

The most important is to control the maximum current drawn by the inverter. This is to protect against large over loads or short circuit fault currents damaging the inverter.

Over-temperature

Temperature sensors are required for protection where moderate overloads below the surge limit cause overheating.

High and Low Battery

Voltage cut-outs are provided on most inverters to prevent damage to the inverter, the battery and the load.

Inverter Power
The output power (wattage) of an inverter indicates how much power the inverter can supply during standard operation. It is important to choose an inverter, which will satisfy a system's peak load requirements.

Surge Capacity
Most inverters are able to exceed their rated wattage for limited periods of time. This is necessary since appliances may require many times their rated wattage during start up. As a rough "rule of thumb", the minimum surge requirement may be calculated by multiplying the required wattage by three.

Inverters Used as Battery Chargers
Some Inverters have the added advantage that they have a built-in battery charger so that when the batteries need charging from an AC source (generator), the current can be fed into the inverter, changed to DC, and then used to charge the batteries.

Stand-by Losses
When there is no load applied to the inverter it rests in what is called "stand-by" mode. Typically inverters use 30-60 milliamps of current (or 1-2 % of rated power) in stand-by mode.
Isolation
The input (DC side) and the output (AC side) need to be isolated.

Control Equipment
Regulators are an essential part of any battery-based electrical system to prevent overcharging and exceeding the recommended discharge of the battery that will result in subsequent damage and reduced life.
Charge Regulator
To prevent overcharging of a battery, a charge regulator is used to sense when the batteries are fully charged and to stop or decrease the amount of current flowing from the energy source to the batteries.

Types of Regulators
Regulators can be broadly classified into the following groups:
1. Shunt or Series Regulators
2. Linear or Switching Regulators
3. Manual or Automatic Regulators
Shunt or Series Regulators
A shunt regulator is one in which the energy source is continually operated at full available power and excess power is "burnt off" in a dummy load. The regulator is installed in parallel with the source and the battery. In wind and hydropower systems they can also act as a load to prevent over speeding of the generator.
A series regulator is connected between the charge source and the battery. Some series regulators may switch the source to an alternative system such as water pumping or auxiliary battery bank.

Linear and Switching Regulators
A linear regulator continuously adjusts the charge supplied to the battery at any given moment to maintain the optimum voltage. A switching regulator is an on/off device that disconnects the charge source completely. In a solar array this may be done in stages to remove part of the array in each step.A switch mode regulator is a high speed switching device that applies pulses of power to the battery terminals. The disadvantage of this type is the complexity of the switching and the difficulty in controlling radio frequency noise. A hysteresis or dual voltage point regulator operates on the battery terminal voltage. When voltage rises to a set point the regulator switches out the charge source. When voltage falls to a predetermined point the charge source is reconnected. This cycling may be very rapid or may be controlled by a timer to set a minimum period.

Manual or Automatic Regulators
The control of the charge comes to a single variable, terminal voltage. The simplest form of control is to measure and respond to terminal voltage. A boost cycle is needed to equalize cell voltages and battery needs to be regularly brought to gassing voltage to stir the gassing voltage and to stir the electrolyte and prevent stratification. Boost cycles are generally manually controlled, and in some advanced systems it is programmed.
Smart regulators are micro processor controlled devices that monitor system parameters against time to give a more accurate picture of battery condition and charging requirements.

Specifying a Regulator
The regulator must be specified to match the system voltage, battery type and load current.

Characteristics of Load
Alternating Current (AC) or Direct Current (DC)
Load components with purely resistive elements in them can be satisfactorily powered using DC current. This means that there is no necessity for the use of an inverter. Resistive loads however tend to use a significant amount more power so their use is not recommended for remote are a power supply systems. To run most appliances it is often simpler to use an inverter to produce AC current and power the appliance circuits with that.

Waveform
In most cases a modified square wave (Figure 9) current is appropriate, but if there are to be appliances with high surge currents a sine wave (Figure 10) inverter may be a better option.
Interference
Some electrical equipment (radios, TV's, computers) may be affected by interference from appliances such as microwave ovens and may not operate as efficiently.

System Sizing
Two major issues arise when designing a system:
-The load put on the system is not constant over the period of one day and the daily load is not constant over a year; and
-The amount of energy available from the renewable energy source may vary from time to time during the day and from day to day during the year.
An approach would be to design a system to produce a certain percentage of the total energy required on a yearly basis and to top up with a back-up generator if there is insufficient energy from the renewable energy source. In all cases the first step in system sizing is to estimate the load placed on the system.

6.5 Photovoltaic Modules
To determine the actual required PV array output, divide the daily energy requirement by the battery round-trip efficiency. This is usually a figure between 0.70 and 0.95 and depends on the columbic efficiency of the batteries in both charging and discharging. Generally 0.95 is used for very efficient batteries installed in good conditions and 0.7 for the least efficient batteries.
Example 1: Daily Load = 100 Ah, Battery Efficiency = 0.9
Array output required = 100 / 0.9 = 111 Ah
To work out the output from the array, it is important to know under what conditions the output will be determined, and need to know what the inclination of the array will be. This is measured in peak sun hours, which is dependent on latitude, season and inclination of the array.
The scenario generally chosen for solar / generator hybrid systems is the yearly average peak sun hours. If tables of peak sun hours are not available they can be determined from the average of daily total global radiation. (To convert daily global radiation (MJ/m2) to peak sun hours divide by 3.6).
The output of the modules will be average annual peak sun hours times the module rating.
Example 2: Under normal operating cell temperature 0 (NOCT)
Average Annual Peak Sun Hours = 5 Module Rate = 5 Amps
Battery Charging Voltage = 14 Volts Output Accuracy = +/- 10%
Current output = 0.9 X 5 Amps = 4.5 Amps
Therefore the guaranteed current will be 90% of the current at 14 volts under NOCT.
To determine the number of modules in the array first work out the number of modules in series (So that the operating voltage is sufficient for battery charging). Divide the system voltage by the nominal operating voltage of each module.
Example 3: System Voltage = 24V
Nominal Operating Voltage of each module = 12 V
Number of modules in series = 24 / 12 = 2
Therefore the number of modules in the array will have to be a multiple of 2.
To determine the number of modules in parallel the array output required (Ah) is divided by the output of each module (Ah).

Example 4: Average Annual Peak Sun Hours at the latitude = 5 hrs
Current Output (from Example 2) = 4.5 Amps
Array Output Required (from Example 1) = 111 Ah
Module output = 4.5 Amps X 5hrs = 22.5 Ah
Therefore number of modules in parallel = 111 Ah / 22.5 Ah = 4.9 (round up to 5)
Therefore the array will consist of 5 parallel strings with two modules in each string.
Sizing and Specifying a Battery Charger and Back–Up Generator
A battery charger converts the AC output to DC for the purpose of battery charging. The battery charger should be selected such that it converts the 240 volt, 50 Hz AC to DC at the required bus voltage of the battery storage bank. It should be able to provide a direct current up to the maximum allowable charge rate of the batteries.
The two critical factors to consider when selecting a battery charger are:
-The system voltage; and
-The maximum rate of charge of the batteries.
Example 6:
Battery Capacity = 875 Ah at the C100 rate System Voltage = 24 V
Capacity at 10 Hour Charging Rate = 662 Ah
Maximum Charging Rate: C10 = 662 Ah
662 / 10 = 66.2 A
There may not be a battery charger with exactly the maximum current specified so a charger with lower current would be chosen. The most likely available charger would be 24 Volt 60 Amps.
Battery bank capacity is usually sized to provide 3-7 days autonomy to a depth of discharge of around 80%.

Selecting a Generator
Example 7: Efficiency of Charger = 60%

Power produced by charger: 60 A X 24 V = 1440 Watts
Input power from generator: 1440 W / 0.60 = 2400 W
A generator with a capacity at or above 2.4 kW will have to be chosen. Alternatively the KVA rating of the battery charger can be used and multiplied by the power factor for the charger.
Example 8: Load: 3.3 kW
Generator Capacity = 2.4 kW (battery charging) + 3.2 kW (loads) = 5.6 kW
Then making allowance for future de-rating of the generator, the size the generator should be increased up to 6 kW.
6.6 Renewable Resource Quality
A renewable resource is judged by its magnitude and consistency. Any site that receives more than 1800 kilowatt-hours per year of solar insulation is considered a good site for a PV system.
An average wind speed of 5.8 m/s is considered a good wind resource. Another factor is the daily match between load demand and energy production from the renewable generators. The better the match the more attractive the renewable energy source becomes, because the power can be supplied directly to the load and losses associated with storing the energy can be avoided.

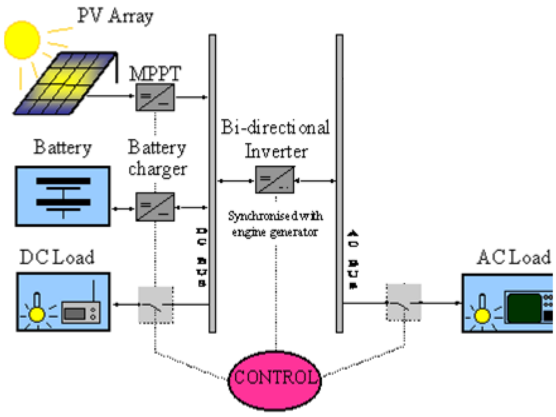


Figure: 6.8. PV Power System.

6.7 Present Condition of Photovoltaic (PV) system:

PV is already the fastest growing industry in the world. But if it is going to play a significant role in future worldwide electricity production, it all comes down to one word – scalability. The PV industry happens to be the fastest growing industry in the world, with a promising chance to remain the fastest growing industry for the next 25 to 50 years. The PV industry worldwide grew at a compound annual rate of 35% during 2000-2009.What is the cause of this enormous growth and why is it expected to continue? The reason is really quite simple. The market demand is enormous and PV has a number of unique characteristics that give it clear and significant advantages over any other source of electrical energy. Photovoltaic (PV) hybrid systems can make a positive contribution to the sustainability of rural communities in developing countries that do not have access to electricity grid. Integration of solar photovoltaic system with diesel generator for remote and rural areas would assist in expanding the electricity access in the tropical region.

6.8 The PV Industry Needs

The PV industry needs to reduce its cost of production. Bottom line, it currently costs too much to produce PV cells. In order to dramatically reduce the cost, the industry must deploy next generation technologies that are scalable to larger volumes that will enable the needed cost reductions. This contradiction is a result of the fact that the market is so vast, and that despite the current tremendous industry growth, it is only the beginning of the industry’s long-term growth curve. Incredible as it may sound the industry actually has the potential to grow at 30% per annum rates for decades. Regardless of this dichotomy, long-term world demand will exceed long term supply (even at current “high” costs) and when future decreases in cost are accomplished the demand will literally soar far beyond the capabilities of current technology. To address this coming demand surge, new next-generation technologies, capable of far greater production volumes, will be necessary; hence process scalability will be needed.

6.9 Solar Power in Bangladesh

Bangladesh is a massively power-deficient country with peak power shortages of around 25%. More than 60% of its people do not have access to the power grid. The country only produces 3500-4200 MW of electricity against a daily demand for 4000-5200 MW on average, according to official estimates. Solar energy is an ideal solution as it can provide gridless power and is totally clean in terms of pollution and health hazards. Since it saves money on constructing electricity transmission lines, it’s economical as well. Little wonder that it is becoming popular in Bangladesh. The number of households using solar panels has now crossed the one million mark, the fastest expansion of solar use anywhere in the world. In 2002, just 7,000 households in Bangladesh were using solar panels, but now more than one million households, or five million people, are benefiting from solar energy.

The Government of Bangladesh has also withdrawn all the import tariff and VAT (Value Added Tax) on the raw materials of solar panels for the current fiscal year. The Government of Bangladesh said that Bangladesh gets about 250 to 300 sunny days on average per year (rainy days are not included). He added that since the maintenance cost is very low, we could massively increase the use of solar power in the country. The solar panel providers in Bangladesh are now expecting the price of batteries and accessories to drastically reduce. In fact, solar panels and accessories imported from countries in the developed world like Germany cost a lot, but the same panels manufactured in China cost much less. The requirements of power in a typical Bangladeshi home are very small, almost 1/10th that of a Western home. The government owned Infrastructure Development Company (IDCOL) has been providing financing for these small solar panel projects in the country.

Fig: 6.9 solar panel of Bangladesh

The Asian Development Bank (ADB) has been at the forefront in funding solar energy in Asian countries like Thailand, India and now Bangladesh. The ADB and the Government of Bangladesh have recently signed technical assistance grant agreements of $3.3 million to provide renewable energy in rural areas with no access to grid electricity. The grant will provide $25 subsidy per Solar Home Systems (SHS) to a total of 80,000 low-income end-users. The assistance will also promote biomass, biogas, and wind as alternative sources of energy. In addition, the grant will help the state-run IDCOL improve its administrative and monitoring capacities. The assistance will support Bangladesh’s efforts to increase access to electricity in remote rural areas and to reduce carbon emissions by overcoming market barriers for renewable energy development’, said by Country Director of ADB’s Bangladesh Resident Mission. IDCOL estimates that each SHS saves at least $61.80 worth of kerosene every year and reduces carbon dioxide emissions by 375 kilograms annually as a result. Therefore, the 80,000 new SHSs to be installed through this grant assistance will bring a reduction of about 27,600 tons of carbon dioxide emissions a year. On the other hand the government also plans to implement a mega solar project by setting up a 500 MW solar panel-based power installation with financial support from the ADB. Such a project will require a huge investment of $2-3 billion according to power ministry officials. As the lead agency, the power ministry has laid out a plan involving nine other ministries to implement this highly ambitious plan. Meanwhile, the Bangladesh Bank has set up a Tk. 200 million (US$ 2.70 million) revolving fund for banks and financial institutions to give loans at low interest in the solar energy, biogas and effluent treatment sectors. A top official of the Bangladesh Bank noted that the lack of institutional financing for renewable energy is impeding effective growth and the use of environment-friendly technology. In the capital city, Dhaka, the power department has set a pre-condition of installing solar panels on buildings applying for new connections. In the villages, solar power is even being used to operate pumps for irrigation. Today both urban city dwellers and villagers in remote areas of Bangladesh are using solar energy.

6.10 Current Electricity Market

The current electricity demand is roughly 4 trillion watts (4 Terawatts or TW) and is growing at approximately 2.5% per year. Current projections place demand somewhere between 11 TW and 18 TW by 2050.To illustrate the tremendous potential of the PV industry and also the current and future demand-supply imbalance facing the industry let’s look at a few macro numbers. For PV to supply only 1% of the demand in 2010, the worldwide PV production capacity would have to be 44 billion watts, which is over 20 times larger than current worldwide capacity. It is obvious that expanding the total industry capacity 20 fold in a few years is impossible, one thing for sure, we MUST set the bar a lot higher.

Note:
Megawatt (MW) = one million watts of electricity
Gigawatt (GW) = one thousand megawatts (one billion watts) of electricity
Terawatt (TW) = one thousand gigawatts (one trillion watts) of electricity

Percentage of Demand (2010) to be met with PV	GW of capacity needed	# Times larger than current worldwide industry capacity
1%	44	20 Times Larger
5%	220	125 Times Larger
10%	440	250 Times Larger

Electricity Demand 2010 vs. Current PV Industry Capacity

The above table shows the enormous potential of PV and how large worldwide PV capacity would have to be compared to current industry capacity, for PV to achieve 1%, 5% and 10% of the worldwide electricity market. At least two points become very clear from the table above: The potential market for PV worldwide is absolutely enormous; new production technologies will be needed to produce far greater volumes at far lower prices if the industry is ever going to make a significant penetration of this huge market. Currently 90%+ of the world's solar cells are manufactured using silicon technology. This technology is over 50 years old and the good news is that it has done an amazing job at dramatically reducing the price of solar cells over the years. The bad news is that the price needs to decrease even more and it cannot do this without technologies that can be scaled up to produce GW and not the current industry MW. Unless the industry develops a manufacturing technology or discovers a new breakthrough technology that is capable of cost effectively producing PV at the GW level, PV can never make a significant contribution to future electricity generation. In addition to the obvious huge business opportunity, there may be other factors that will necessitate the rapid development of the PV industry and a host of new next-generation clean technologies. This future increase in demand may not be able to be addressed by fossil fuel sources for a number of reasons that, for the most part may be beyond our control. The future of the PV industry and how significant of a role it will play is a question of scale. We have to start thinking big and we have to start right now. We need to accelerate our development of next generation technologies, with far greater production capacity, so that we will have far lower cost of production. There are a number of other macro and micro factors that will also be needed, which I will cover in a subsequent article. But the bottom line from a macro point of view is quite simply. Limitations to addressing this growth via fossil fuels:

Peak Oil: Short term, Peak Oil is approaching, when worldwide demand will exceed supply permanently. This may cause a rapid and permanent rise in the price of oil and natural gas that will make them uneconomical at best and unavailable at worst.

Global Warming: Longer term, global warming may drastically limit our use of fossil fuels to generate electricity. This will be especially true of generation of electricity with coal, which currently supplies over 50% of the electricity generated in the U.S. and is a very significant contributor to carbon to our atmosphere.

6.11 Concentrating Solar Power

Concentrating Solar Power (CSP) systems use lenses or mirrors and tracking systems to focus a large area of sunlight into a small beam. The concentrated heat is then used as a heat source for a conventional power plant. A wide range of concentrating technologies exists; the most developed are the parabolic trough, the concentrating linear Fresnel reflector, the Stirling dish and the solar power tower. Various techniques are used to track the Sun and focus light. In all of these systems a working fluid is heated by the concentrated sunlight, and is then used for power generation or energy storage. A parabolic trough consists of a linear parabolic reflector that concentrates light onto a receiver positioned along the reflector's focal line. The receiver is a tube positioned right above the middle of the parabolic mirror and is filled with a working fluid. The reflector is made to follow the Sun during the daylight hours by tracking along a single axis. Parabolic trough systems provide the best land-use factor of any solar technology.

The SEGS plants in California and Acciona's Nevada Solar One near Boulder City, Nevada are representatives of this technology. Compact Linear Fresnel Reflectors are CSP-plants which use many thin mirror strips instead of parabolic mirrors to concentrate sunlight onto two tubes with working fluid. This has the advantages that flat mirrors can be used which are much cheaper than parabolic mirrors, and that more reflectors can be placed in the same amount of space, allowing more of the available sunlight to be used. Concentrating linear Fresnel reflectors can be used in either large or more compact plants. The Stirling solar dish combines a parabolic concentrating dish with a Stirling engine which normally drives an electric generator. The advantages of Stirling solar over photovoltaic cells are higher efficiency of converting sunlight into electricity and longer lifetime. Parabolic dish systems give the highest efficiency among CSP technologies. The 50 kW Big Dish in Canberra, Australia is an example of this technology. A solar power tower uses an array of tracking reflectors (heliostats) to concentrate light on a central receiver atop a tower. Power towers are more cost effective, offer higher efficiency and better energy storage capability among CSP technologies. The Solar Two in Barstow, California and the Planta Solar 10 in Sanlucar la Mayor, Spain are representatives of this technology. The role which renewable energy-based solar power systems play in meeting the increased demand for clean electricity and assisting economic development is not fully appreciated, and has largely been ignored in national plans.As the world becomes more dependent on technology and transportation, the interest in renewable energy sources such as solar energy is growing. Politicians, economists, scientists, entrepreneurs, and many other professionals have noticed this change and are making changes to accommodate green energy such as wind, solar, and hydro power.

6.12 Merits and Demerits:

The most important merit of solar power is its ability to be renewed. We will never run empty on sun reserves, but oil reserves are drying up faster every day. Because oil takes millions of years to form, chances are that green energy sources such as solar power are going to lead the way in the energy industry in the near future. One of the main merits of solar power is its predictability and reliability. Solar power is when electricity is derived from the sun, which is very consistent. It is very easy to predict what times of the day the sun will be shining, how long it will shine. Some other green energy sources can't boast this type of reliability. Wind power, for instance, is much less predictable and is not constantly blowing in most areas. Another major merit of solar power is that scientists are always finding new and improved methods of harnessing energy from the sun's rays. By improving the plates used to absorb the rays, more energy can be produced with smaller panels. This allows an area to create more electricity than ever before, and the outlook looks good for those communities that are becoming more reliant on solar power. Wind power and hydro power have the demerit in this regard. Although their technology can be improved upon to generate more electricity, it is not as easy for those scientists to develop new methods. Ever heard about the greenhouse effect? This is basically when heat gets trapped in the gas "bubble" around the earth. When polluting gases are released into the atmosphere, this bubble gets thicker and can trap more heat than the earth is meant to keep. This leads to global warming, which can destroy the earth as we know it. A solar power merit is that it is non-polluting. Unlike burning coal or oil, carbon dioxide and other greenhouse gases are not let into the atmosphere from using the sun's energy. This is one of the most important advantages to using this resource, as our children and children's children will need all the help they can get to reduce the greenhouse effect. Solar cells are very resilient and normally last for several years before they need replacing (or perhaps even longer). This leads to large money and time savings, allowing the energy company to continue producing new cells to install new solar farms around the world.Solar panels are relatively easy to install. As opposed to wind turbines, it isn't too difficult to make your own solar panels and install them yourself. That said, you may want to hire an expert anyways to save yourself time and frustration.

Although there are a number of great things about solar power, there are also demerits to solar power. The primary drawback (and main reason why it's not more widely used) is the expensive price tag. Compared to oil or natural gas, solar panels are very expensive to produce and set up. This means several years are required to get a positive return on the investment, and in these times where money is tight, this can be hard to swallow. Another demerit of solar power is the number of limitations it has. For example, very cloudy regions of the world or those that don't get much direct sunlight do not benefit as well as desert or tropical regions. Also, you wouldn't want your car to break down just because there was no sun outside to give the battery some juice. We all have to drive at night, so better batteries to store this power much are produced. Although the sun's times are very predictable, the panels collecting the energy are not very efficient. Although today's solar panels are much more efficient than they were 20 years ago, we still have a long way to go to be able to easily power a house or business using solely energy from the sun.One major demerit to solar power is that anything obstructing the panel's path to the sun will hinder the amount of electricity created. This means that solar panels work best in wide open areas, but most cities and suburbs, where panels are needed the most due to high energy demands, are not wide open.

Summary

Although there are a number of merits and demerits of solar power, we must learn to accept it and improve it- our future depends on it.

VII. Discussions and Conclusions

7.1 Applications of Wireless Power Transmission (WPT)

Generating power by placing satellites with giant solar arrays is Geosynchronous Earth Orbit and transmitting the power as microwaves to the earth known as Solar Power Satellites (SPS) is the largest application of WPT. Another application of WPT moving targets such as fuel free airplanes, fuel free electric vehicles, moving robots and fuel free rockets. The other applications of WPT are Ubiquitous Power Source (or) wireless power Source, wireless sensors and RF Power Adaptive Rectifying Circuits (PARC).

7.2 Advantages and Disadvantages

Wireless Power Transmission system would completely eliminates the existing high-tension power transmission line cables, towers and sub stations between the generating station and consumers and facilitates the interconnection of electrical generation plants on a global scale. It has more freedom of choice of both receiver and transmitters. Even mobile transmitters and receivers can be chosen for the WPT system. The cost of transmission and distribution become less and the cost of electrical energy for the consumer also would be reduced. The power could be transmitted to the places where the wired transmission is not possible. Loss of transmission is negligible level in the Wireless Power Transmission; therefore, the efficiency of this method is very much higher than the wired transmission. Power is available at the rectenna as long as the WPT is operating. The power failure due to short circuit and fault on cables would never exist in the transmission and power theft would be not possible at all.

The Capital Cost for practical implementation of WPT seems to be very high and the other disadvantage of the concept is interference of microwave with present communication systems.

7.3 Sustainability of Wireless Power Transmission

Wireless power brings many interesting possibility when it comes to limiting the environmental impact of electronics. Batteries and chargers contribute millions of pounds to American landfills. In 2006 134 million phones were at the end of life. Not all of these phones were recycled and many of their batteries made it waste depositories.[36].The harmful corrosive chemicals contribute to the soil and may end up contributing to acid rain or other harmful phenomenon. Also we dispose many different tethered electrical chargers, which contain plenty of precious copper, aluminum and nickel. Sustainability definition normally includes "satisfying the needs of the present generation without compromising the ability of future generations to meet their own needs." Not only chargers but if distribute power from the grid powerlessly this would save tons of copper used to run power to remote areas and metropolises. Wireless power could potentially improve the quality of life by reducing the inordinate amount of both injury and destruction that can be caused by excessive wires. A single wireless power router could provide power to multiple sources without any of the mess that the multiple extension cords would cause. According to the United States Consumer Product Safety Commission every year there are about four thousand injuries due to tripping over electric cords ranging from simple lacerations and sprains to fractions and contusions. In addition to the large amount of people that are injured it is believed by the Consumer Product Safety Commission that an addition 50 people are killed and 270 injured in over 3,300 fires caused by extension cords. [37] By making better use of wireless transmission of power the quality of life and safety of thousands of people can be greatly improved.

7.4 Future of Wireless Power Transmission

Although wireless technology is still very much in a developmental stage it has incredible consumer potential. Although in the past attempts at making wireless power a large consumer product has not been given much attention, consumers today are more likely to be inclined to look into this topic. According to MIT Professor John Joannopoulos, ""In the past, there was no great demand for such a system, so people did not have a strong motivation to look into it, over the past several years, portable electronic devices, such as laptops, cell phones, iPods and even household robots have become widespread, all of which require batteries that need to be recharged often.[25] Given the extreme marketability of the product it is very possible that it will continue to grow and in the next twenty years there will be incredible improvements in the amount of wireless technology available to consumers. In five years it is highly possible that wireless power will have made its debut as a large consumer product. If experimentation increases in five years time there is a good chance that the size of the technology will shrink and that it will be able to work over larger areas. Combined with an increased efficiency this could be all that it takes to make wireless power transmitters a household item in five years time. Within ten years it is even possible to have experimentation to begin on wireless technology on a much larger scale, and it is very likely that in twenty to thirty years there may be the technology to power a whole house and possibly whole towns with this technology. Wireless technology is a process of the future and it has great potential for improvement and future consumer implementation.

7.5 Feasibility of Solar Power in Bangladesh

From the comparative analysis of the current and projected cost of electricity from conventional and renewable sources it is clear that solar power is the most expensive. Due to other compelling reasons beyond the immediate cost of production Germany, China and other developed nations are promoting and subsidizing solar power to supply more than 20 per cent of their total power usage. The question is why? Nuclear power is politically very sensitive and its technology is very difficult to obtain. By far it is the most risky in terms of damage it can cause in time of man-made or natural disasters. Recent nuclear disaster in the aftermath of earthquake and tsunami in Japan and past experience like Chernobyl accident are forcing the developed countries to reevaluate the reliability and safety of electricity generation using nuclear technology. Coal and gas reserves are continuously depleting, and these are not environmentally friendly due to the resulting green house effect. Hydropower is very good, but few countries have sufficient and suitable inland water bodies to install hydroelectric plants. Limited availability of organic waste and vegetation restricts the widespread use of biomass energy. A variety of promising technologies have been proposed to capture the tremendous amount of thermal energy and the wave motion energy of ocean water. However, the technologies and the designs are still undergoing demonstration testing at the research and development stage. Fluids drawn from the deep earth for geothermal plants carry a mixture of gases, notably carbon dioxide (CO_2), hydrogen sulfide (H_2S), methane (CH_4) and ammonia (NH_3). These pollutants contribute to global warming, acid rain, and noxious smells if released. Wind power seems to be the most viable and least expensive renewable source of energy, but still wind power is not widely recommended for countries like Bangladesh due to lack necessary wind profile. A number of researchers, organizations and Bangladesh Power Development Board (BPDB) performed series of studies to generate wind profile data in Bangladesh. It has been reported that the wind speed in Chittagong, Cox's Bazar, Kuakata, Moheshkhali, Feni and Noakhali coastal regions are greater than 6.5 m/s. During day times (8 a.m. to 7 p.m.) wind speeds are about 30 to 40 per cent higher than the average values. These wind speeds in the coastal regions are suitable for both water pumping and electricity generation. However, inland wind plants would not be viable because of the low wind speed and variable wind profile in areas far away from the coast. The technical feasibility of solar power in Bangladesh depends on availability of technology and sunlight profile across the country. Our public and private sectors are currently in good financial position to gather necessary expertise and technology to build commercial scale and rooftop solar plants. We just need appropriate policy undertaking. Let us look at the sunlight profile issue in Bangladesh. Our climatic conditions and the geographical position are very favorable for solar power. Unfortunately, no formal study has been done to report accurate data on sunlight profile throughout the year in Bangladesh. For a reasonable estimate we can take sunlight data of our neighboring states of India as the basis. National Renewable Energy Laboratory (NREL) of India reports that with about 300 clear and sunny days in a year, India's theoretical solar power reception, on only its land area, is about five Petawatt-hours per year (PWh/yr) (i.e. 5 trillion kWh/yr). The daily average solar energy incident over Indian land varies from 4 to 7 kWh/m2 with about 1500–2000 sunshine hours per year (depending upon location), which is far more than current total energy consumption. For example, assuming only 10 per cent efficiency of solar plants, this would still be a thousand times greater than the domestic electricity demand projected for India in 2015. According to the study conducted by NREL of India, the daily direct normal solar index is around 4.5kWh/m2 in the states of West Bengal, Assam, Meghalaya and Tripura, which are the areas surrounding Bangladesh with almost identical climatic conditions and geographical location. We can reasonably predict that the average available incident solar power in Bangladesh will be close to 4.5kWh/m2, and with 15 per cent efficiency of currently available commercial solar plants we can produce 0.67kWh of electricity from a solar panel of one square meter size. If we select a 100m by 100m land, and keep 33 per cent of the area for supporting structure, equipments and connections to the solar panels we can install solar panels of total 6700 square meter on that land, which will give us 10MWh of electricity. This is a very good number compared to commercially operating solar plants in different countries. Based on the above discussion we can propose that for Bangladesh small and medium size solar power plants distributed all over the country would be a very promising solution.

7.6 Compare and Contrast

As a result of an increase in consumer demand for electronic devices, many researchers have begun to develop technology that could power these electronic devices without the use of wires. Even today's most technologically advanced innovations are bound by a relatively short battery life. Through magnetism, resonance, or microwaves many different avenues exist for research and development in regard to wireless power. We will use our paper as an opportunity to investigate different technologies and review them based on their merits. Consumer devices need to accomplish a task not only cheaply but also safely. This paper will allow a better understanding of the exact science behind wireless power transmission. Also it will show how this science relates to products and their environment. Wireless power transfer via magnetic resonant coupling is experimentally demonstrated in a system with a large source coil and either one or two small receivers. Resonances between source and load coils are achieved with lumped capacitors terminating the coils. A circuit model is developed to describe the system with a single receiver, and extended to describe the system with two receivers. With parameter values chosen to obtain good fits, the circuit models yield transfer frequency responses that are in good agreement with experimental measurements over a range of frequencies that span the resonance.

Resonant frequency splitting is observed experimentally and described theoretically for the multiple receiver system. In the single receiver system at resonance, more than 50% of the power that is supplied by the actual source is delivered to the load. In a multiple receiver system, a means for tracking frequency shifts and continuously retuning the lumped capacitances that terminate each receiver coil so as to maximize efficiency is a key issue for future work. Resonance-based wireless power delivery is an efficient technique to transfer power over a relatively long distance. This technique typically uses four coils as opposed to two coils used in conventional inductive links. In the four-coil system, the adverse effects of a low coupling coefficient between primary and secondary coils are compensated by using high-quality ( ) factor coils, and the efficiency of the system is improved. Unlike its two coil counterpart, the efficiency profile of the power transfer is not a monotonically decreasing function of the operating distance and is less sensitive to changes in the distance between the primary and secondary coils. A four-coil energy transfer system can be optimized to provide maximum efficiency at a given operating distance. We have analyzed the four-coil energy transfer systems and outlined the effect of design parameters on power-transfer efficiency. Design steps to obtain the efficient power-transfer system are presented and a design example is provided. A proof-of-concept prototype system is implemented and confirms the validity of the proposed analysis and design techniques. In the prototype system, for a power-link frequency of 700 kHz and a coil distance range of 10 to 20 mm, using a 22-mm diameter implantable coil resonance-based system shows a power-transfer efficiency of more than 80% with an enhanced operating range compared to 40% efficiency achieved by a conventional two-coil system.

VIII. ACKNOWLEDGEMENT

The authors would like to thanks Asst. Prof. Mr.Ebad Zahir for his technical assistance and support regarding this paper.

REFERENCES

[1] A. Kurs, et al., "*Wireless power transfer via strongly coupled magnetic resonances*," SCIENCE, vol. 317, pp. 83-86, July 2007.

[2] Y. Tak, et al. "*Mode-based analysis of resonant characteristics for near-field coupled small antennas*," IEEE Antennas and Wireless Propagation Letters, vol. 8, pp. 1238-1241, 2009.

[3] T. Ishizaki, et al. "*Comparative study of coil resonators for wireless power transfer system in terms of transfer loss,*" IEICE Electronics Express, vol. 7, no. 11, pp. 785-790, 2010.

[4] N. Oodachi, H. Kudo, K. Ogawa, H. Shoki, S. Obayashi T. Morooka," *Efficiency improvement of wireless power transfer via magnetic resonance using the third coil",* ISAP2010, paper ID 52, Macao, China Nov. 2010.

[5] NEC WIN Professional TM," *Antenna Analysis Software Version 1.1,"* Nittany Scientific Inc., California, 1997.

[6] Aleksandar Marinicic, Djuradj Budimir, "*Tesla's Contribution to Radiowave Propagation*", IEEE TELSIKS (2001), Page No- 327-331.

[7] Nikola Tesla, U.S.Patent 1119732 (1914).

[8] W.C.Brown, "*The History of Power Transmission by Radio Wave*", IEEE Trans.vol-32, Page no-1230-1248.

[9] Saurab Sood, S.Kullanthasamy, M.Shahidehpour, "*Solar Power Transmission: From Space to Earth*", IEEE Trans. (2005).

[10] Peter E. Glaser, "*Energy for the Global Village*", IEEE Trans. (1995)

[11] T.Vanderelli, J.G.Shearer and J.R.Shearer, U.S.Patent 7027311 (2006).

[12] Popular Science, "*Splashpower Splashpad*", Best of What's new, (2003).

[13] Andre kurs, Aristeidis karalis, Robert Moffatt, J.D. Joannopoulos, Peter Fisher,Marin Soljacic, "*Wireless Power Transfer via Strongly Coupled Magnetic Resonances", Research Article,"Science*",vol-317, Page no-83 to 85.

[14] Aristeidis karalis, J.D.Joannopoulos, Marin Soljacic, "*Efficient Wireless non-radiative mid range energy transfer*", "Annals of Physics", Page No-34-48.

[15] Andre Kurs, "*Power Transfer Through Strongly Coupled Resonances*", M.Sc. thesis, Massachusetts Institute of Technology, (2007).

[16] K.O'brian, G.Schieible, H.Gueldner, The 29th Annual Conference of IEEE1, 367 (2006).`

[17] Nigel P.Cook, S.Dominiak and H.Widmen, U.S Patent 102292 (2009) and 72629 (2009).

[18] Chunbo Zhu, Kai Liu, C.Yu, Rui Ma, H.Cheng, "*Simulation and Experimental Analysis on Wireless Energy Transfer Based on Magnetic Resonances*", IEEE Vehicle Power and Propulsion Conference, (2008).

[19] H.A.Haus, W.Huang, "*Coupled Mode Theory*" IEEE Proceedings, vol-79, Page No-1505-1518.

[20] H.Haus, "*Waves and Fields in Optoelectronics",* Prentice Hall Edition, (1984).

[21] Vic Christianto and F.Smarandache, "A *Note on omputer Solution of Wireless*

Energy Transmit via Magnetic Resonance", "Progress in Physics", Vol-1, (2008).

[22] Andre Kurs, Aristeidis Karalis, Robert Moffatt, J. D. Joannopoulous, Peter Fisher, Marin Soljačić .30 March 2007. "*Wireless Power Transfer via Strongly Coupled Magnetic Resonance*." http://www.sciencemag.org/cgi/rapidpdf/1143254?ijkey=94ff.Ay4jRMqU&Key type=ref&siteid=sci. Science. Accessed: January 31 2008.

[23] Brown, William C. "*The history of wireless power transmission*." Solar Energy. Vol. 56. London. Permagon, p. 3-21.

[24] Castelvecchi, Davide. 15 November 2006."Wireless energy may power electronics." MIT TechTalk, p. 8.

[25] Chien, Kuei-Yuan. "*Wireless Transmission of Electricity – Development and Possibility*." Sixth International Symposium Nikola Telsa. 18-20 October 2006.

[26] "*Goodbye wires... MIT experimentally demonstrates wireless power Transfer*" 7 June 2007. http://www.physorg.com/news100445957.html Accessed: 27 February 2008. [27] Joannopoulos, J.D. and Aristeidis Karalis and Marin Soljacic. April 17, 2007. Efficient wireless non-radiative mid-range energy transfer". http://arxiv.org/pdf/physics/0611063 Accessed: 22 February 2008.

[28] "Flat, Flexible, Wireless Power Source Can Go Anywhere". 23 May 2007. http://www.physorg.com/news99145812.html Accessed: 25 February 2008.

[29] "*Physics promises wireless power*." 2006. Bbc.co.uk. http://news.bbc.co.uk/2/hi/technology/6129460.stm. Accessed: January 30 2008.

[30] Tsuyoshi Sekitani, Makoto Takamiya, Yoshiaki Noguchi, Shintaro Nakano, Yusaku Kato, Kazuki Hizu, Hiroshi Kawaguchi, Takayasu Sakurai, and Takao Someya. "*A large-area flexible wireless power transmission sheet Using Printed Plastic MEMS Switches and Organic Field-Effect Transistors*" http://icdesign.iis.u-tokyo.ac.jp/2006_22a.pdf . Accessed January 31 2008.

[31] Wilson, Tracy V. "*How Wireless Power Works*" howstuffworks.com http://electronics.howstuffworks.com/wireless-power1.htm Accessed: February 27 2008.

[32] "*1,301 Fluorescent Bulbs Lit Solely by Magnetic Fields*." 2008. Gizmodo.com. http://gizmodo.com/361390/1301-florescent-bulbs-lit-solely-by-magnetic-fields.

[33] Resource Conservation Challenge Update. Environmental Protection Agency. Marc 2008. http://www.epa.gov/epaoswer/osw/conserve/resources/rcc-rpt3.pdf Accessed March 31 2008.

[34] "*Extension Cords Fact Sheet*" United States Consumer Product Safety Commission.http://www.epa.gov/epaoswer/osw/conserve/resources/rcc-rpt3.pdf Accessed Marc 31 2008.

[35] http://cleantechindia.wordpress.com/2008/07/16/indias-electricity-transmission-and-distribution-losses/

[36] Nikola Tesla, My Inventions, Ben Johnston, Ed., Austin, Hart Brothers, p. 91, 1982.

[37] Nikola Tesla, "*The Transmission of Electrical Energy Without Wires as a Means for Furthering Peace,*" Electrical World and Engineer. Jan. 7, p. 21, 1905.

[38] The Electrician (London), 1904).

[40] W.C. Brown, J.R. Mims and N.I. Heenan, "*An Experimental Microwave-Powered Helicopter",* 965 IEEE International Convention Record, Vol. 13, Part 5, pp.225-235. 48, pp. 111-120, 2000.

[41] T-WYoo and K. Chang, "*Theoretical and experimental development of 10 and 35 GHz rectennas,*" IEEE Trans. Microwave Theory Tech., vol. 40, pp. 1259-1266, 1992.

[42] P. Koert and J.T. Cha, "*35 GHz rectenna development,*" in Proc. 1st Annu. Wireless Power Transmission Conf., San Antonio, TX, 1993, pp. 457-466.

[43] Brown, W.C, "*The History of the Development of the Rectenna*" Proc. Of SPS microwave systems workshop, pp.271-280, Jan 1980.

[44] www.howstuffworks.com (How Micro Ovens Work – A Cooking Oven for the 21st century. By Gabriel Gache)

[45] J.C. Lin, "*Biological aspects of mobile communication fields,"* Wireless Networks, vol. 3, pp. 439-453, 1997.

[46] M. Onda, M. Fujita, Y. Fujino, N. Kaya, K. Tomita, and MYamada, "*A stratospheric stationary LTAplatform concept and ground-to-vehicle microwave power transmission tests,"* in 37th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, 1999, pp. 1-7.

[20] P. Koert and J.T. Cha, "*35 GHz rectenna development,*" in Proc.1st Annu. Wireless Power Transmission Conf., San Antonio, TX, 1993, pp. 457-466.

[47] T.-W. Yoo, "*Experimental and theoretical study on 35 GHz RF-to-DC power conversion receiver for millimeter-wave beamed power transmission*," Ph.D. dissertation, Dept. Of Electrical Engineering, Texas A&M Univ., Dec. 1993

[48] "CES Best of 2007"

[49] www.tgdaily.com

[50] Brown., W. C. (September 1984). "*The History of Power Transmission by Radio Waves*". Microwave Theory and Techniques, IEEE Transactions on (Volume: 32, Issue: 9 On page(s): 1230-1242 + ISSN: 0018-9480). http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=1132833.

[51] *POINT-TO-POINT WIRELESS POWER TRANSPORTATION IN REUNION ISLAND* 48th International Astronautical Congress, Turin, Italy, 6-10 October 1997 - IAF-97-R.4.08 J. D. Lan Sun Luk, A. Celeste, P. Romanacce, L. Chane Kuang Sang, J. C. Gatina - University of La Réunion - Faculty of Science and Technology.

[52] Matsumoto, H.N. Kaya, I. Kimura, S. Miyatake, M. Nagatomo, and T. Obayashi, *MINIX Project toward the Solar Power Satellites --- Rocket experiment of microwave energy transmission and associated plasma physics in the ionosphere*, ISAS space energy symposium, pp 69-76, 1986.

[53] J.J. Schelesak, A. Alden and T. Ohno, *A microwave powered high altitude platform*, IEEE MTT-S Int. Symp. Digest, pp - 283-286, 1988.

[54] "*Goodbye wires*…". MIT News. 2007-06-07. http://web.mit.edu/newsoffice/2007/wireless-0607.html.

[55] L.W. Epp, A.R. Khan, H.K. Smith and R.P. Smith, "*A compact dual-polarized 8.51-GHz rectenna for high-voltage (50 V) actuator applications*," IEEE Trans. Microwave Theory Tech., vol.

[56] Haus, H. A. (1984) *Waves and fields in optoelectronics*. Englewood Cliffs: Prentice hall, pp. 197-234.

[57] Karalis, A., Joannopoulos, J.D., and Soljacic, M. (2008) *Efficient wireless non-radiative mid-range energy transfer*. Annals of Physics, 323, pp. 34-48.

[58] Kurs, A., Karalis, A., Moffatt, R., Joannopoulos, J. D., Fisher, P., and Soljacic, M. (2007) *Wireless power transfer via strongly coupled magnetic resonances*. Science, 317, pp. 83-86.

[59] Robertson, J. (2008) *How to power up without plugging in*. Available from: http://www.msnbc.msn.com/id/26349363/ [Accessed on 28 Oct 2009].

[60] Zhang, F., Liu, X., Hackworth, S. A., Sclabassi, R. J., and Sun, M. (2009a) *In Vitro and In Vivo Studies on Wireless Powering of Medical Sensors and Implantable Devices*. Proceedings of the Fourth Annual IEEE-NIH Life Science Systems and Application, 9-10 Apr, Bethesda, Maryland, USA.

[61] Zhang, F., Liu, X., Hackworth, S. A., Micke, M. H., Sclabassi, R. J., and Sun, M. (2009b) *Wireless power transfer in the home environment via strongly coupled magnetic resonance. Proceedings of the 2009 Internation*al Symposium On Digital Life Technologies: Human-Centric Smart Living Technology, 28-30 May, Tainan, Taiwan.

[62] Advanced Energy Systems, 1998. Eastern Indonesia Hybrid Energy Project, Advanced Energy Systems LTD, No. 04/SP/P/PLDT/BPPT/IV/1998, Australia.

[63] Advanced Energy Systems (AES), 1978. The Static Power Guide, Australia.

[64] Clay, B., 2003. *Design Example for a Standalone SHS*, Institutional Capacity Building on Renewable Energy Training in Pacific Island Developing States, SOPAC, Fiji.

[65] Cloin, J., 2003. *Hybrid System Simulation, SOPAC*, Suva, Fiji (Appendix 2, this report).

[66] Environment Meteorological Consultants, 1997. *Southern Pacific Wind and Solar Monitoring Project Final Report*, Energy Division, Forum Secretariat, Suva, Fiji.

[67] Forum Secretariat Energy Division, 1996. Glossary of Common Energy and Related Terms, Fiji.

[68] Islam, S.M., 1999. *Improving Operational Cost in a Hybrid System by Optimal Sizing and Control Design*, A Short Course On: PV/Diesel/ Hybrid Systems, Australian Cooperative Research Centre For Renewable Energy, Curtin University of technology, Australia.

[69] Karkkainen, S., Elmahgary, Y., 1988. *Energy Storage Systems in Developing Countries*, Natural Resources and the Environment Series Volume 21, The Technical Research Centre of Finland (VTT), UNEP, ESCAP, Cassell Tycooly, London.

[70] McKenzie, E., 2003. *Notes on Economic Evaluation, Institutional Capacity Building on Renewable Energy Training in Pacific*

Island Developing States, SOPAC, Fiji. [Unpublished note, SOPAC Secretariat]

[71] Mandawali, E., 1996.*PV/Diesel Hybrid Power System. Radio and Transmission Group*, Telikom Training College, LAE PNG. Nabouwalu Hybrid Project documents, Department of Energy, Fiji.

[72] Nayar, C., 1999. A Short Course On: *PV/Diesel/ Hybrid Systems, Australian Cooperative Research Centre For Renewable Energy*, Curtin University of technology, Australia.

[73] Pacific Power, 1999. *Centralized Village Power Systems: Economic Comparison*, Pacific Volume 7, Number 3, Pacific Power Association, Suva, Fiji Islands.

[74] S.E.I.A.A., 1995. *Remote Area Power Supply Systems, An Introduction, Solar Energy industries Association, Australia*.

[75] Seru, N.D., Nakavulevu, P., Narayan, P., 1999.*Renewable Energy development Programme*, DOE, Fiji.

[76] SOPAC, 2002. *Pacific Energy Newsletter*, Issue 3, SOPAC, Suva.

[77] Vega, L., 2003. Nabouwalu, Vanua Levu *Hybrid Power System Design, Training on Renewable Energy Resource Assessment*, 26-30 May, 2003, Department of Energy, Fiji.

[78] Wardrop, N., 1995. *Hybrid Energy systems, Rural Electrification Workshop*, Forum secretariat Energy Division, Suva, Fiji.

[79] Wichert, B., Nayar, C.V., Lawrance, W.B., 1999. *Photovoltaic-Diesel hybrid energy Systems for Off-grid Rural Electrification, Centre for Renewable Energy Systems* Technology Australia.

[80] Curtin University of Technology, western Australia.