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# Developments in Wireless Power Transfer Using Solar Energy

*Himanshu Dehra*

## Abstract

This chapter presents state-of-the-art and major developments in wireless power transfer using solar energy. The brief state-of-the-art is presented for solar photovoltaic technologies which can be combined with wireless power transfer (WPT) to interact with the ambient solar energy. The main purpose of the solar photovoltaic system is to distribute the collected electrical energy in various small-scale power applications wirelessly. These recent developments give technology based on how to transmit electrical power without any wires, with a small-scale by using solar energy. The power can also be transferred wirelessly through an inductive coupling as an antenna. With this wireless electricity we can charge and make wireless electricity as an input source to electronic equipment such as cellphone, MP3 Player etc. In harvesting energy, technologies of ambient solar radiation like solar photovoltaic, kinetic, thermal or electro-magnetic (EM) energy can be used to recharge the batteries. Radio frequency (RF) harvesting technologies are also popular as they are enormously available in the atmosphere. The energy converted to useful DC energy which can be used to charge electrical devices which need low power consumption. The chapter has also presented a parallel plate photovoltaic amplifier connected to a potentiometer as a Resistance-Capacitance (RC) circuit power amplifier. The effect of inductance and resulting power transfer has been theoretically determined in the RC amplifier circuit. The electrical and thermal properties and measurements from a parallel plate photovoltaic amplifier were collected to analyze the unbalanced power transfer and inductance in a nonlinear RC circuit amplifier using equivalent transfer functions. The concept of Wireless Information and Power Transfer using Electromagnetic and Radio Waves of Solar Energy Spectrum is also briefly outlined.

**Keywords:** wireless power transfer, solar energy, energy harvesting, photovoltaics, amplifier

## 1. Introduction

Wireless power transfer (WPT) is defined as the transmission of electrical power without wires through various methods and technologies using time-varying electric, magnetic, or electromagnetic fields. The development of various technologies for wireless power transfer is being taken widely across the power electronics domains. There are applications which include microwaves, solar cells, lasers, and electro-magnetic waves' resonance in wireless power transfer. With wireless power transfer, the electrical devices are continuously charged without the use of power cord. The three types of wireless power transfer systems can be described by microwaves, resonance, and solar cells. From the power source to a receiver in an electrical

device or gadget, microwaves can be used to send electro-magnetic radiation. The method of resonance can be applied at certain frequencies to cause an object to oscillate by electro-magnetic radiation. These oscillations can be used to transfer energy between two oscillating sources. The satellite in space with solar cells can be used to capture the solar energy and transmit this energy back to earth. This method would involve the conversion of radio waves frequencies into electrical power and electrical power into radio waves frequencies. The main purpose of the solar photovoltaic system is to distribute the collected electrical energy in various small-scale power applications wirelessly. These recent developments give technology based on how to transmit electrical power without any wires, with a small-scale by using solar energy.

Wireless power transfer (WPT) using solar energy technology is having vast applications. The ability of technology is to transfer power efficiently, safely over distance can improve gadgets and products by making them more reliable, climate and environment benign. Wireless power transfer (WPT) can be used in various applications for example in automatic wireless charging, direct wireless power supply of devices such as cellphones, loudspeakers, digital picture frames, flat screen TV's, home theater accessories etc. [1]. The power can also be transferred wirelessly through an inductive coupling as an antenna. With this wireless electricity we can charge and make wireless electricity as an input source to electronic equipment such as Handphone, MP3 Player etc. In harvesting energy, technologies of ambient solar radiation like solar photovoltaic, kinetic, thermal or electro-magnetic (EM) energy can be used to recharge the batteries. Radio frequency (RF) harvesting technologies are also popular as they are enormously available in the atmosphere. The energy converted to useful DC energy which can be used to charge electrical devices which need low power consumption.

This chapter outlines the recent developments of wireless power transfer using solar energy. The rest of the chapter contains brief history of the development of wireless power transfer. Various methods and technologies used in wireless power transfer are outlined. The State-of-the-Art of Wireless Power Transfer using Solar Energy is also described along with the literature review. The later part of the chapter contains novel concept of transmitter design of a parallel plate photovoltaic amplifier device integrated in a Building. The design of a receiver using radio waves for wireless information and power transfer is also briefly discussed. Conclusions and equations for design of a transmitter and a receiver are provided in the later part of the chapter.

## **1.1 History**

The presence of electro-magnetic waves by devising a mathematical model is predicted by James C. Maxwell in 1864. The Poynting Vector would play an important role in quantifying the electromagnetic energy (John H. Poynting, 1884). Heinrich Hertz first succeeded in showing experimental evidence of radio waves by his spark-gap radio transmitter in 1888, which was bolstered by Maxwell's theory. The wireless power transfer was started by the prediction and evidence of the radio wave in the end of 19th century. Wireless power transfer of electrical power was pioneered by Nikola Tesla [2]. He conducted experiments on wireless power in 1891 at his "experimental station" at Colorado. A small incandescent lamp by means of a resonant circuit grounded on one end was successfully lighted by Nikola Tesla [3]. The lower end connected to the ground and the upper end free with a coil outside his laboratory. The current was induced in the three turns of wire wound around the lower end of the coil and the lamp was lighted. For trans-Atlantic wireless telephony and demonstration of wireless electrical power transfer by means of Wardenclyffe tower, which was designed by Tesla. The modern development of microwave power transmission which dominates research and development of wireless power transfer

today was achieved by William C. Brown. In the early 1960s Brown invented the rectenna which directly converts microwaves to DC current. He demonstrated its ability in 1964 by powering a helicopter from the solely through microwaves.

## 1.2 Methods

**Radio and Microwave:** Typically, in the microwave range, wireless power transfer via radio waves can be made over longer distance power beaming, with shorter wavelengths of electromagnetic radiation with more directional component. To convert the microwave energy back into electricity, a rectenna may be used. Conversion efficiencies exceeding 95% have been realized with rectenna. For the transmission of energy from orbiting solar power satellites to Earth and the beaming of power to spacecraft leaving orbit, power beaming using microwaves has been considered [4].

**Electromagnetic Transmission:** Electromagnetic waves can also be utilized for wireless power transfer. Power beaming can be employed by converting electricity into light, such as a laser beam, then firing this beam at a receiving target, such as a solar cell on a small aircraft, power can be beamed to a single target.

**Induction:** For the transfer of wireless electrical power, the principle of mutual induction between two coils can be used. Electromagnetic coupling between the two coils is used to transfer the energy. The simplest example of how mutual induction works is the transformer, where there is no physical contact between the primary and the secondary coils.

**Electrodynamic Induction:** Resonant inductive coupling for wireless power transfer resolves the main problem associated with non-resonant inductive coupling. It has dependence of efficiency on transmission distance. The transmitter and receiver inductors are tuned to a mutual frequency and the drive current is modified from a sinusoidal to a non-sinusoidal transient waveform with the use of resonant coupling. Pulse wireless power transfer occurs over multiple cycles. Significant wireless power may be transmitted over a distance of up to a few times the size of the transmitter with this method.

**Electrostatic Induction:** For wireless energy transfer involving high frequency alternating current potential differences transmitted between two plates or nodes, capacitive coupling is utilized with an electric field gradient or differential capacitance between two elevated electrodes over a conducting ground plane.

## 1.3 Technologies

**Microwave Transmitter:** The frequency range of choice for transmission is achieved by means of microwaves. Presently, an efficiency of 76% is possible using current technology for microwave power transmission. The waves must be focused so that all the energy transmitted by the source is incident on the wave collection device for increasing transmission efficiency. The high cost of transmitters and the relative low efficiency of current optical and infrared devices makes higher frequencies impractical. The most common transmitters for microwaves are klystron, traveling wave tube (TWT) and magnetron. The klystron has been the DC to microwave converter of choice however it is also somewhat expensive. The TWT is far too expensive and power restrictive making it impractical for the task of power transmission. The use of magnetrons because they are cheap and efficient is investigated by many researchers. The power transmission is more lenient to frequency fluctuations than the communication systems in magnetrons frequency output but is not as precisely controllable as the klystron or TWT. An array of magnetrons to be used as the transmitter can be one of the more common R & D investigation proposal. In range of 300 W to 1 kW magnetrons are already mass produced for



microwave ovens, it is one of the main advantages to using many smaller magnetrons as opposed to a few klystrons.

The generation of microwave power in the microwave power source and its output power is managed by electronic restrain circuits on the transmission side. To match the impedance between the transmitting antenna and the microwave source, a tuner is attached. Based on the direction of signal propagation by Directional Coupler, whose function is to divide the attenuated signals. The transmitting antenna emits the power uniformly through free space to the receiver antenna. An antenna receives the transmitted power and translates the microwave power to DC power on the receiving section. For setting the output impedance of a signal source equal to the rectifying circuit, both impedance matching circuit and the filter is provided. The Schottky barrier diodes which converts the received microwave power into DC power are connected in the rectifying circuit.

#### **Use of Microwave Power Transmission in Solar Power Satellites (SPS):**

For transmitting power to earth stations, solar power generating satellites can be launched into space. Based on this idea, which was first proposed in 1968 based on experiments carried out in terrestrial laboratories. At high earth orbit in geosynchronous location, the SPS satellites are put in the orbits. This feature enables them to receive light almost whole year by up to 99% of the yearly time. A facility of a large rectenna array built on the Earth is for collecting the incoming microwaves. The satellite is required to be built with a retrodirective transmitter for maintaining a good lock on the rectenna. This helps in locking on to a pilot beam emanated from the ground station. Most of the research is done in the 2.4 GHz to 5.8 GHz range. Therefore, there are some spectrum regulatory issues to deal with their use. Also, the retro directive antenna system is unproven with present technology. The microwave beam could veer off target and can microwave some unsuspecting family. Therefore, this is the cause of the health concern [5].

**Magnetic Resonance:** In this technology, an oscillator is designed to generate the carrier signal for transmitting the power. Usually, oscillators are not intended to deliver the power, because a power amplifier is required to the oscillator for amplification of the oscillating signal. The output power to the transmission coil is transferred by the power amplifier. For receiving the transmitted power, a receiver coil is built. Since the power received at the receiver side is having an alternating current. Thus, a rectifier is needed for rectification of the AC voltage. An electric load is connected to the receiving coil to complete the circuit [6].

**WiTricity:** The new technology called WiTricity is based on using coupled resonant objects [1]. With the same resonant frequency, two resonant objects manage to exchange energy efficiently, while interacting weakly with extraneous off-resonant objects. The resonant nature of the witricity system guarantees the strong interaction between the sending unit and the receiving unit, while the interaction with the rest of the environment is weak. The design consists of two copper coils, each a self-resonant system. One of the coils, attached to the power source can be a solar power and is termed as the sending unit of the witricity. The irradiation of the environment with electromagnetic waves oscillates the space around it with a non-radiative magnetic field oscillating at MHz frequencies. The non-radiative field intervenes the power exchange with the receiving coil, which is built for the purpose of creating resonance with the field.

## **2. State-of-the-art: wireless power transfer using solar energy**

Solar cells are semiconductor devices in which incident sunlight releases electric charges so they can move across the semiconductor freely and thus generate an

electric field to light a bulb or power a motor. The whole phenomenon of producing an electric field of voltages and currents across the solar cell is known as the photovoltaic effect [6]. The incident light for solar cells—sunlight—is freely available and abundant. The intensity of sunlight near the surface of the earth is at the most in the range of one thousand watts per square meter known as 1 sun. The cost must be considered in calculating the cost of the electricity produced by solar cells as the area occupied by the photovoltaic modules power generating system may be relatively large. The cost per unit output is the decisive factor relative to that of alternative power sources, for acquiring, installing, and operating the photovoltaic system. This is dependent on this sole factor that determines whether the solar cells will be used to supply electricity in a given situation. Solar cells are economically competitive with alternative sources in their use in terrestrial applications. The examples of these applications include pumps, communication and refrigerated devices located in remote areas far from existing transmission and distributed power lines. The markets for solar cells are growing rapidly as the cost of power from conventional sources rises, and as the cost of solar cells reduces because of technological improvements with economies at a bigger scale manufacture.

**Working of a Solar Cell:** The working of a solar cell depends upon the phenomenon of photo-electricity, i.e., the liberation of electrons by light falling on a body. The application of this photo-electric phenomenon to semi-conductors such as silicon has proved to be of great use. To displace an electron from a fixed position in the material and make it move freely in the material, a vacant electron position or 'hole' is created in the material by light waves when they strike a semiconductor material with sufficient energy. If a neighboring electron leaves its site to fill the hole site, this hole acts as positive charge and can move this electron. The electron-hole pairs are differentiated by the voltage in the cell material, and this creates a current. By adding small amounts of dopants and impurities to the pure material and by joining two semiconductor materials, an intrinsic voltage may be created. The silicon becomes electron-rich and is referred to as 'n-type' silicon when impurities such as phosphorous are introduced into this silicon. Excess holes are created when impurities such as boron give rise to 'p-type' silicon. A free charge leaks across the common boundary of these n-type and p-type silicon (one electron rich and the other electron-deficient) and becomes fixed as ions in the region near to the boundary, when these two oppositely charged semiconductors are in contact. At the interface, the fixed (but opposite) ions create an electric field that sends free electrons one way and free holes the other side. No current flows in the solar cell, when no light falls on its surface i.e., in the dark. A current will flow as long as the solar cell is illuminated which can supply electricity to an external load circuit. The current from the solar cell passes directly through the load circuit. The current generated can be changed by the power-conditioning equipment to alternating current at the voltage and current levels different from those provided by the solar cells. The sub-systems of the PV module system include energy-storage devices such as concentrated lenses, batteries and mirrors that focus the sunlight onto a smaller and hence less costly semiconductor solar cell. If concentration system is utilized, a tracking subsystem may be required to keep the array pointed at the sun throughout the day.

**Maximum power point tracking:** Maximum power point tracking (MPPT) is used to maximize the power output from wind turbines and photovoltaic (PV) solar systems. PV solar systems exist in several different configurations with a solar inverter, which is connected directly to the electrical grid. A second adaptation which is called the hybrid inverter. In this hybrid inverter, the most basic version sends power from the solar panels directly to the DC-AC and splits the power at the inverter, where a percentage of the power goes to the grid and the remainder goes to

a battery bank. The third type uses a dedicated PV inverter that features the MPPT in which the inverter is not connected at all to the grid. The power flows directly into the battery bank in this configuration. The micro inverters are deployed, one for each PV panel, which are a variation on these configurations. The efficiency of solar PV system by up to 20% by the use of microinverter. The grid-connected power as well as solar PV power and branching off power for battery charging is achieved by incorporating a new MPPT algorithm that is equipped with specialty inverters which serve these three functions,

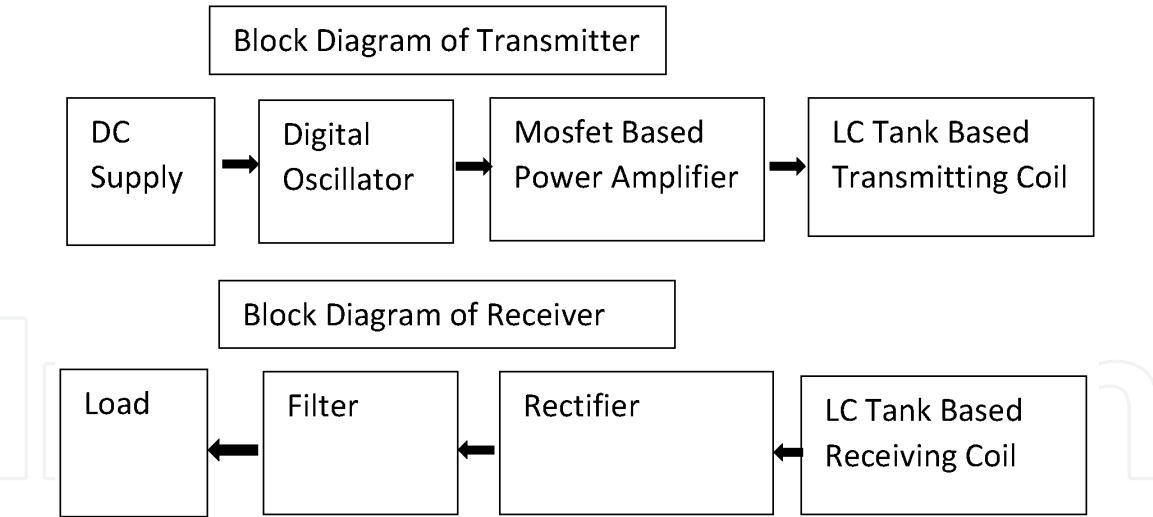
The application related to solar photovoltaic systems contains these MPPT apprehensions. A non-linear output efficiency which can be analyzed based on the I-V curve of the solar cells establishes a complex relationship between temperature and total resistance that produces across solar cells. The output of the PV cells and application of the proper load to obtain maximum power for any given environmental conditions is achieved by the purpose of the MPPT system. MPPT devices are connected into solar photovoltaic system for providing voltage or current conversion, filtering, and regulation for driving various loads, including power grids, batteries, or motors. Solar power inverters are used to convert the DC power to AC power after utilizing MPPT.

**Solar Photovoltaic System Technology for Wireless Power Transfer:** The solar photovoltaic panels can be installed on the façade or roofs. These solar photovoltaic panels convert the sunlight into the direct current (DC) power. The electric current is added or drawn from the electric batteries by means of installing the charge controller, which limits the rate of the current. The batteries are one of the most important parts of the solar power system. The charge controller helps in protecting the batteries from overvoltage and overcharging. This helps in increasing the life span of the batteries. From the solar photovoltaic panels, the DC power is transmitted to the inverter. In the inverter, it is converted into alternating current (AC) power.

The phase locked loop oscillator with a Power Amplifier is connected to the solar inverter. A step up/down transformer is connected to this end section. The generation of an output signal whose phase is related to the phase of the input signal is achieved by means of the phase locked loop oscillator. There is generation of a periodic signal by means of the phase locked loop oscillator. The comparison of the phase of that signal with the phase of the input periodic signal and corrects the oscillator to keep the phases matched is achieved by means of the phase detector. The power amplifier is used to achieve high amplification of the signal. The stepping up or stepping down the signal, which can be done according to the application is achieved by means of the transformer which is connected to the end section of the amplifier. In the AC line, this alternating current is then transmitted. For powering the connected load or other domestic devices, the power from these AC lines is achieved by means of wireless power transfer.

The principle of witrlicity can be applied into this scenario [1]. To transfer wireless power between two electromagnetic resonant objects, Witrlicity can be used which is based on strong coupling. This method is different from other methods like air ionization, microwaves, and induction. The witrlicity system consists of transmitters and receivers. These contain magnetic loop antennas critically tuned to the same frequency. Due to the operation in the electromagnetic near field, the receiving devices must be no more than the quarter-wavelengths from the transmitter. The witrlicity uses near field inductive coupling through magnetic fields like those found in transformers. These tuned magnetic fields generated by the primary coil can be arranged to interact actively with matched secondary windings in distant equipment. These magnetic fields are far from more-weakly with any surrounding objects or materials such as radio signals or biological tissue [6–13].





**Figure 1.**  
*Simplified block diagram for wireless power transfer using solar energy.*

**Working of a Transmitter:** The input from mains is given to the power and frequency controller. The output of this system is given to MOSFET (metal–oxide–semiconductor field-effect transistor)/IGBT (insulated-gate bipolar transistor). The objective of using the MOSFET/IGBT is for conversion of DC power to AC power. It is also used for amplifying square wave at the gate input. The voltage transmitted to the transmitting coil generates magnetic field around it. The capacitor, which is connected to the coil in parallel helps in achieving the resonating circuit. The magnetic field get induced in the receiving coil at the point of the resonant frequency of receiving coil matches with the resonant frequency of the transmitting coil. Different values of “L” and “C” for resonant frequency are used for the matching purpose. To match the resonant frequency of the receiver and the transmitter coil, the switches to vary the time periods of the square wave by controlling the frequency at output can be used [14].

**Working of a Receiver:** The receiving coil comes in the range of the magnetic field of the transmitting coil. This helps in achieving the voltage across the transmitting coil, which gets induced in the receiving coil because of mutual inductance. This also helps in matching of resonance frequency at the received voltage is in AC power form. Here the AC power is converted into DC for DC load, where rectifier circuit can be used to provide constant DC at the output for driving the load. And if the load is AC power load then it can be given directly to the output.

A simplified block diagram for wireless power transfer using solar energy technology is illustrated in **Figure 1** [14].

### 3. Literature review: wireless power transfer (WPT) using solar energy

Only few relevant papers which highlight solar energy based wireless power transfer are briefly discussed here. Zambari et al., investigated the development of wireless energy transfer module for solar energy harvesting [11]. They studied the module of wireless energy transfer (WET) for interaction with the ambient solar energy. The main objective was to distribute the collected electrical energy from a solar panel module to in house loads appliances wirelessly. The investigations were carried out on the solar panel module with 240 W, 30 V, Poly Crystalline Silicon Photovoltaic solar panel. The design of the WET module was based on magnetic resonance technology. This technology uses two sub-unit modules development;



driving circuit and two coils mutually inducted to transfer energy in a suitable resonant frequency. With the advantage of nearly 99% efficiency theoretically, class-D RF power amplifier was used as the driving circuit for transmitted coil switching [11].

Fareq et al., studied the wireless power transfer by using solar energy [12]. They developed the project based on electrical power without any wires, with a small-scale by using solar energy. The power is transferred wirelessly through an inductive coupling as an antenna. The experiments were conducted and the wireless power transfer can be transfer energy up to 10 cm. with efficiency 0–10 cm; 98.87%–40% [12]. Ojha et al., investigated solar energy based wireless power transfer [13]. They reviewed on wireless power transfer (WPT) using renewable source i.e. solar energy. The principle behind WPT used was inductive coupling wherein an electric field is generated thus transmitting power from transmitter to receiver. The paper has highlighted the important use of components like a solar panel, rechargeable battery, booster circuitry, and load. Wireless transmission of power to work up a load was highlighted in the paper [13]. Lakshmi M. K., et al. investigated wireless power transmission through solar power generation [14]. The phenomenon of transfer power using a renewable source, without using wired medium. This paper mainly focused on combining both wireless and solar technologies together with use of the principle through coupled resonant objects for the transferring electricity. The overall goal of this paper is to design and implement a clean power generation and wireless power transmission system which can be used as a standard means for charging any electronic gadget [14].

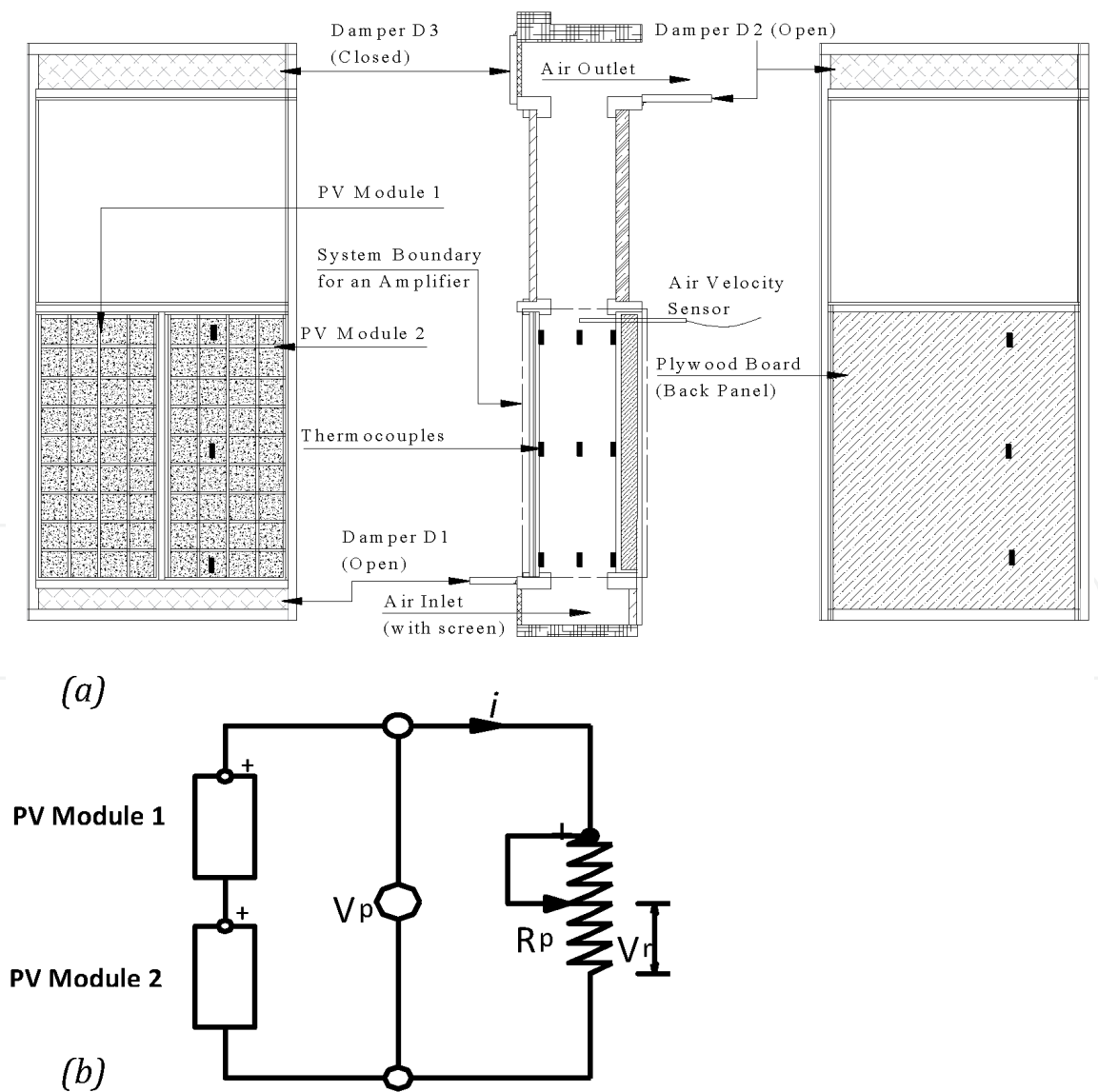
Maqsood et al., investigated wireless power transmission using solar based power satellite technology [15]. The wireless electricity (Power) transmission (WET) was focal point of their research and they presented the concept of transmitting power wirelessly to reduce transmission and distribution losses. The wired distribution losses are 70–75% efficient. The paper also highlighted the benefits of using WET technology specially by using Solar based Power satellites (SBPS) and also focused on how we make electric system cost effective, optimized and well organized [15]. Keerthana et al., investigated Wireless Power Transfer Using Rectenna [16]. The Radio frequency (RF) harvesting technologies were highlighted in the paper. The RF harvesting technologies receive and convert the useful DC energy and can further be used to charge electrical devices which need low power consumption. The paper investigated a microstrip square patch antenna operating at 2.45 GHz. It was fabricated on a low-cost FR4 substrate having a dielectric constant of 4.4 with a thickness of about 1.2 mm. The L-shaped matching network was designed for maximum power transfer between the antenna and the rectifier. The HSMS-2850 zero bias Schottky diode was used as a rectifier. The RF-DC rectification was done with an efficiency of 42.8% at -7 dBm at 2.45 GHz [16].

#### **4. Transmitter design: a parallel plate photovoltaic amplifier device integrated in a building**

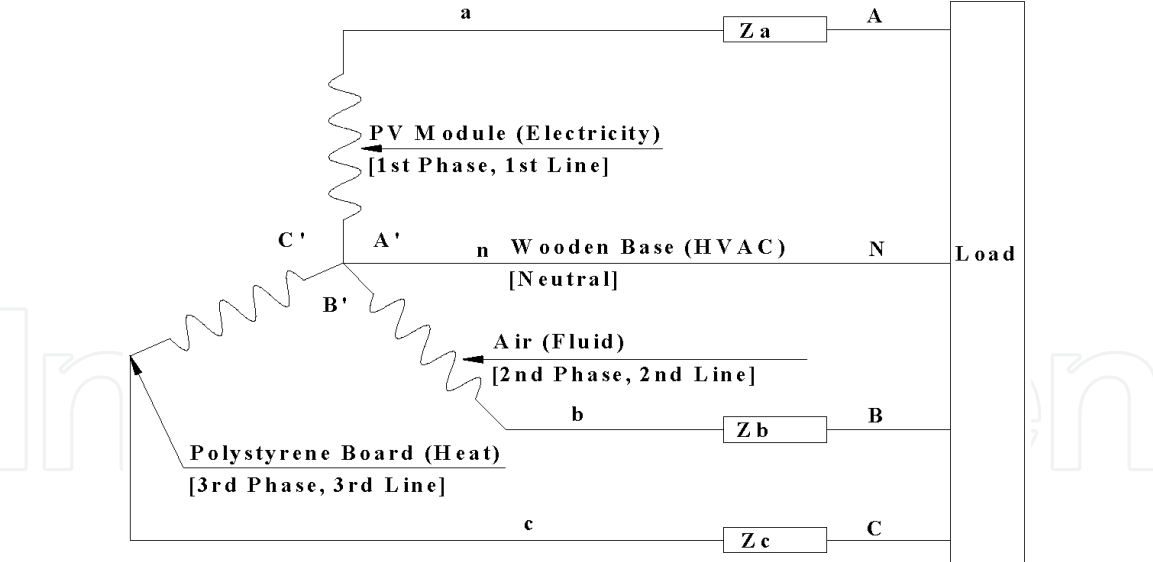
A parallel plate photovoltaic device connected to a potentiometer is analyzed as a star connected 3-Phase Resistance-Capacitance (RC) circuit amplifier. The effect of inductance and resulting power transfer has been determined in the RC circuit amplifier constituting of a parallel plate photovoltaic device. The analysis has also discussed from the electrodynamics point of view, power transfer and effect of induction losses in a 3-Phase RC circuit amplifier constituting of a parallel plate photovoltaic device. The theory of the sinusoidal steady-state response was

applied in performing the analysis of the circuit, because of the advantage of representing a periodic function in terms of a sinusoidal exponential function. The full-scale experimental setup for a parallel plate photovoltaic device connected to a potentiometer was installed in an outdoor room facility located at Concordia University, Montréal, Canada [17–34]. The analysis has been performed on the basis of the accepted unified theory for stresses and oscillations, as proposed by the author [27]. The experimental setup is illustrated in **Figure 2** [17]. A pair of glass coated photovoltaic (PV) modules forming a parallel plate duct with a plywood board and connected to a potentiometer was used to build an amplifier. A wire-wound variable resistor with resistance up to  $50\ \Omega$  was a wire-wound circular coil with a sliding knob contact acted as a potentiometer for the circuit [17]. This potentiometer was used to vary electrical resistance across connected PV modules without interrupting the current. A star connected RC circuit amplifier with a parallel plate photovoltaic device connected to a potentiometer was built (**Figure 3**).

**A Photovoltaic (PV) Device connected to a potentiometer:** A parallel plate photovoltaic device connected to a potentiometer was used for establishing characteristics of this PV device by varying electrical resistance with rotation of knob of



**Figure 2.** Schematic of experimental setup for a parallel plate photovoltaic device connected to a potentiometer: (a) location of sensors; (b) electrical circuit diagram.



**Figure 3.**  
*A star connected 3-phase generation using a parallel plate photovoltaic device.*

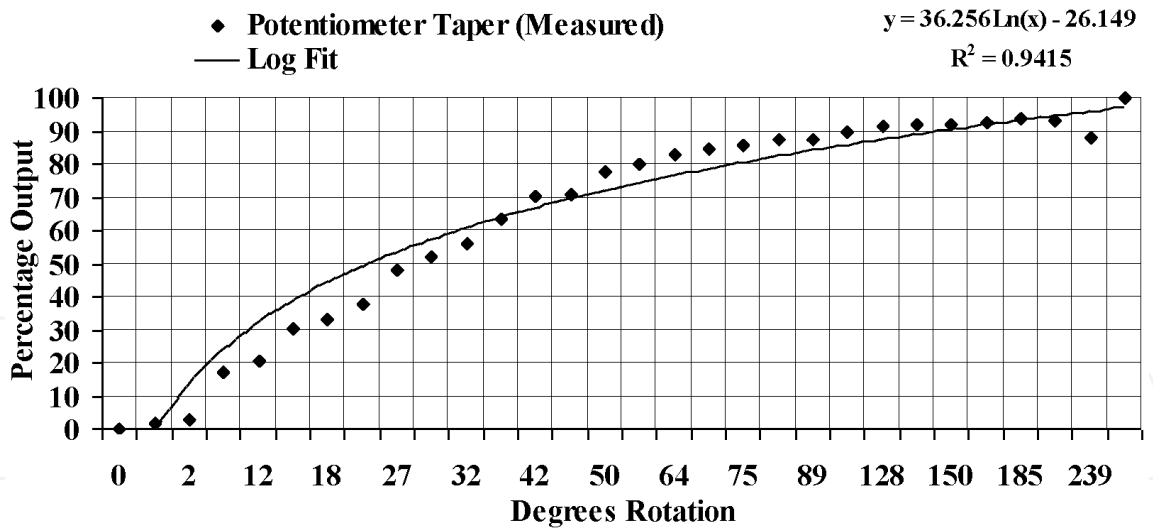
Rotation	Volts	Amps	Watts	Rotation	Volts	Amps	Watts	Rotation	Volts	Amps	Watts
240°	18.7	—	—	83°	16.3	0.935	15.23	30°	9.7	1.577	15.21
239°	16.5	0.331	5.461	75°	16.0	1.014	16.26	27°	9.0	1.587	14.33
201°	17.4	0.414	7.195	69°	15.8	1.100	17.38	21°	7.1	1.583	11.24
185°	17.5	0.454	7.940	64°	15.5	1.165	18.04	18°	6.2	1.573	9.831
162°	17.3	0.513	8.885	55°	15.0	1.302	19.53	17°	5.7	1.578	9.026
150°	17.18	0.550	9.449	50°	14.5	1.386	20.05	12°	3.9	1.567	6.257
142°	17.19	0.582	10.00	43°	13.2	1.503	19.79	10°	3.2	1.553	4.840
128°	17.1	0.640	10.93	42°	13.1	1.493	19.49	1.5°	0.5	1.593	0.807
107°	16.8	0.750	12.51	37°	11.9	1.536	18.26	1°	0.3	1.59	0.426
89°	16.4	0.884	14.45	32°	10.5	1.567	16.42	0°	—	1.643	—

**Table 1.**  
*Sample electrical measurement results with varying resistance of potentiometer.*

a potentiometer [17]. For determining electric power output with a series electrical circuit connection of a pair of vertically inclined PV modules installed on a wooden frame, the current–voltage measurements were obtained. The electrical measurement results of currents, voltages and power with varying electrical resistance of potentiometer are presented in **Table 1**. The results of the power output from a potentiometer with rotation of circular knob are illustrated in **Figure 4**. The phenomenon of photovoltaic amplification has been observed from the graph of **Figure 4**. The gain in steady state electrical for a photovoltaic device is a factor of its volume or resistance. This operational characteristic is similar to the operation of a loudspeaker.

5. Electrical parameters for the RC circuit amplifier

*Capacitance:* The capacitance of a parallel plate photovoltaic device with air as a dielectric medium was calculated to be 91.2 picofarads.



**Figure 4.**  
*Potentiometer taper as a function of percentage voltage output.*

*Resistance:* The electrical resistance of various components were calculated as: glass coated PV modules were approximated as 5.3 k $\Omega$ , air was approximated as 1200 M $\Omega$ , and plywood board was approximated as 26.5 Tera  $\Omega$ . The total equivalent electrical resistance of a parallel plate photovoltaic device was approximated as: 5.3 k $\Omega$ .

*Time Constant:* The time constant, which is product of resistance and capacitance, was calculated to be: 0.5 microseconds. The frequency with this time constant was calculated to be 2 MHz.

*Capacitive Reactance:* The capacitive reactance was calculated to be: 872.5  $\Omega$ .

*Impedance:* The impedance of the circuit was calculated to be: 5.4 k $\Omega$ .

*The Phase angle  $\theta$ :* The phase angle between capacitance and reactance was calculated to be 9°.

*The Phasor representation:*  $Z = 5.300 - j 0.8725 = 5.4 \text{ k}\Omega \angle -9^\circ$ .

*Capacitive Heating:* The joule law gives instantaneous power absorbed by the capacitive impedance and is converted to heat. The heat capacities under critical operation of buoyancy-induced hybrid ventilation were calculated to be 59.6 kJ, 0.755 kJ and 510.7 kJ for PV module, air and plywood board respectively [28]. The total average value of joule heating for the parallel plate photovoltaic device was calculated to be 571 kJ.

*Induction Losses:* The induction losses due to thermal storage effect in the parallel plate photovoltaic device was calculated to be 15.9 KJ [28].

*Power Factor:* The power factor was calculated to be  $\cos \theta = 0.911$  lag.

*Current function ( $i_2(t)$ ):* Using the current function,  $i^2(t) = I_m^2 \sin^2(\omega t + \theta)$ , the effective (root mean square) value of current was calculated to be 10.4 amps and maximum value of current was calculated to be 14.71 amps.

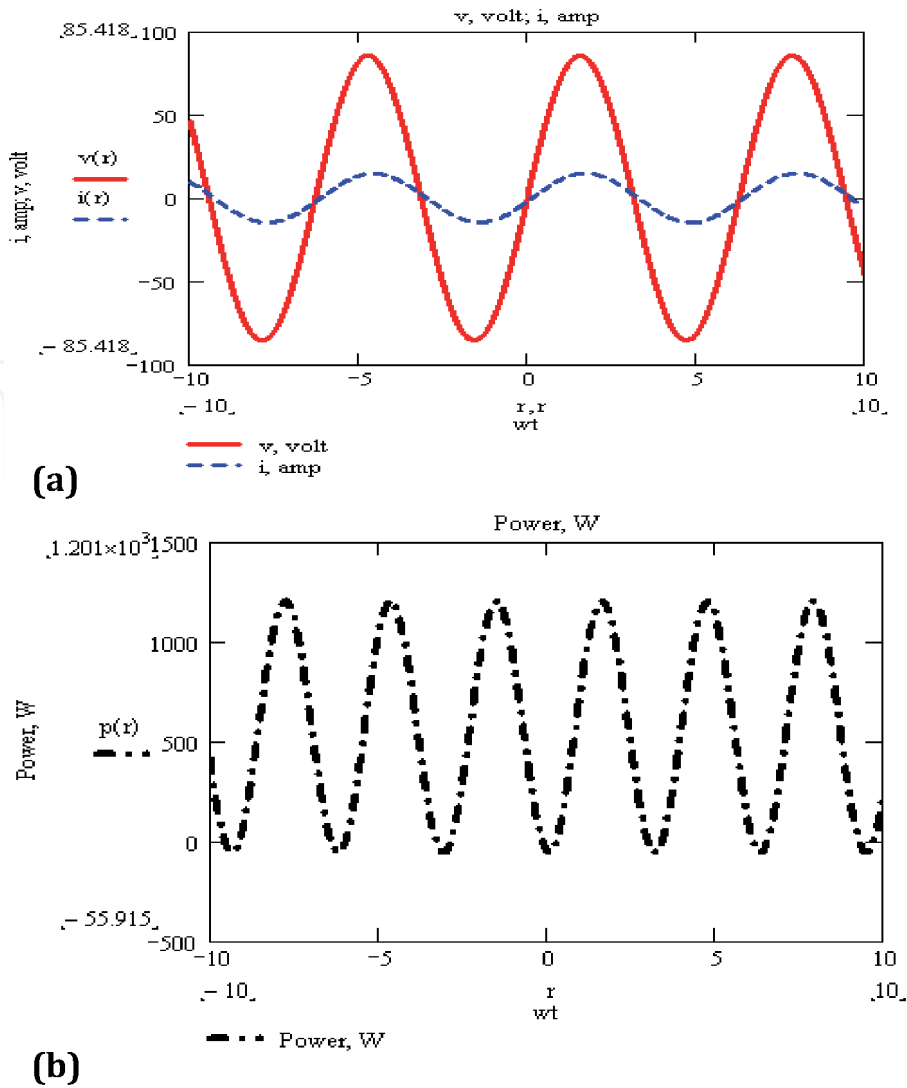
*Voltage function:* The voltage function is defined as per the sine wave:  $v = V_m \sin(\omega t)$ . The effective value of the voltage was calculated to be 60.4 volts and maximum value of the voltage was calculated to be 85.42 volts.

*Power function:* The instantaneous power is given by the expression:

$$p(t) = \frac{V_m I_m}{2} \cos(\theta) - \frac{V_m I_m}{2} \cos(2\omega t - \theta) \tag{1}$$

*The Plots:* The time diagram for current, voltage is plotted in **Figure 5(a)**. The time diagram for power is plotted in **Figure 5(b)**.





**Figure 5.**  
Time diagrams: (a) voltage and current; (b) power in the RC circuit amplifier.

### 5.1 Discussions on power transfer and effects of inductance

*Capacitive Reactance and Resistance in Series:* The losses that appear in capacitive circuits are lumped in a resistor connected in series with the capacitor.

*Capacitance and Resistance in parallel:* When a sine waveform voltage is applied across a capacitor and a charging current of sine waveform is transmitted across the circuit. The alternating current source, which is a sine waveform voltage, if applied at a uniform rate, is responsible sinusoidal response of the charging current in the capacitor. The motion of the charging current is transmitted through the capacitor, corresponds to the electron flow in the wires connecting the capacitor to the alternating current source. The alternating current source is responsible for development of the electric stress in the dielectric between the plates of the capacitor. Electron flow does not occur through the capacitor. The electrons flow around the capacitor circuit in one cycle, which causes a negative charge to build up on one place, and a corresponding positive charge on the other, and the next cycle causes a reversal of the polarity of the charges on the plates. Thus, the effective impedance which the capacitor offers to the flow of alternating current can be relatively low while the insulation resistance which the dielectric offers to the flow of direct current is extremely high.

*Power Transfer:* With no voltage or charge, the electrons in the dielectric between the capacitor plates rotate around their respective nuclei in normally circular orbits.

When the capacitor receives a charge the positive plate (PV Module) repels the positive nuclei and at the same time the electrons in the dielectric are strained toward the positive plate and repelled away from the negative plate (Plywood Board). This distorts the orbits of the electrons in the direction of the positive charge. During the time the electrons are changing from normal to the strained position there is a movement of electrons in the direction of the positive charge. The movement constitutes the displacement current in the dielectric. When the polarity of the plate reverses, the electron strain is reversed. If a sine-wave voltage is applied across the capacitor plates the electrons will oscillate back and forth in a direction parallel to the electrostatic lines of force. Displacement current, is a result of the movement of bound electrons, whereas conduction current represents the movement of free electrons.

The **Figure 5(b)** shows that the instantaneous power is negative whenever the voltage and current are of opposite sign. However, as has been illustrated in the **Figure 5(b)** that positive area of  $p(t)$  energy exceeds the negative area. Therefore, the average power is finite. Since the angle,  $\theta$ , is small between current and voltage, the negative area of  $p(t)$  energy become very small. During the first quarter cycle (from  $0^\circ$  to  $90^\circ$ ) the applied voltage rises from slightly negative value to a maximum and the capacitor is receiving a charge. The power curve is positive during this period and represents energy stored in the capacitor. From  $90^\circ$  to  $180^\circ$ , the applied voltage is falling from maximum to slightly negative value and the capacitor is discharging. The corresponding power curve is negative and represents energy returned to the circuit during this interval. The third quarter cycle represents a period of charging the capacitor and the fourth quarter represents a discharge period.

*Induction Losses:* The induction losses due to thermal storage amount to 1.5% in comparison to the capacitive heating [28, 29]. When a circuit containing a coil or source of energy is energized with direct current, the coil's effect in the circuit is evident only when the circuit is energized, or when it is de-energized. However, when the inductive circuit is supplied with alternating current, the induction losses are continuous and much greater than when it was supplied with direct current. For equal applied voltages, the current through the circuit is less when alternating current, is applied than when direct current is applied. The alternating current is accompanied by an alternating magnetic field around the area of the source of energy, which cuts through the area of the source of energy in the circuit. Most of the applied voltage appears across inductance,  $L$ , with little remaining for the load in the circuit. In a circuit possessing inductance only, the true power is zero. The current lags the applied voltage by  $90^\circ$ . The areas of induction losses above the X axis represent positive energy and the areas below the X axis represent negative energy [28–34].

## 6. Development of a receiver using radio waves for wireless information and power transfer

The focus of the current research is to expedite the efforts for development of a receiver using radio waves for wireless information and power transfer using solar energy spectrum. Liang Liu et al. investigated transmit beamforming for simultaneous wireless information and power transfer using radio frequency (RF) transmission [35]. It is essential to have Radio frequency (RF) transmission enabled wireless power transfer (WPT) to power energy-restricted wireless systems (e.g., sensor networks), where dedicated energy transmitters are deployed to broadcast RF signals to charge low-power electric devices (e.g., sensors and RF identification

(RFID) tags), as it is a cost-effective solution. Radio Frequency (RF)-based wireless power transfer (WPT) can provide continuous and controllable power supply, and thus is applicable to more energy-demanding applications [35]. Radio frequency (RF) signals have been widely used in wireless communications as the carrier for wireless information transfer (WIT) for several decades.

A query thus arises that whether we can utilize RF signals more efficiently for both WPT and WIT at the same time with a new technique called simultaneous wireless information and power transfer (SWIPT) [35]. The SWIPT is developed by considering a single-antenna point-to-point channel, where the trade-off between the achievable rate for WIT and the received energy for WPT is investigated that the single-antenna receiver can utilize the same received RF signals for both information decoding (ID) and energy harvesting (EH) at the same time without any loss. However, this assumption is difficult to realize in practice since existing information receivers (IRs) and energy receivers (ERs) are separately designed with distinct circuit structures, and as a result, each of them cannot be used to decode information as well as harvest energy at the same time. The two basic receiver structures have been widely adopted in the literature [35].

Time-Switching receiver (TS) switches between an information decoder and an energy harvester over time. This technique is the simplest way to implement SWIPT by using off-the-shelf commercially available circuits for information decoding (ID) and energy harvesting (EH), respectively. It is crucial to determine their operation modes (ID or EH) over time for TS receiver. This is based on their communication and energy requirements, as well as the channel conditions [36]. Power-Splitting receiver (PS) splits its received signal into two portions with one for information decoding (ID) and the other for energy harvesting (EH). In this technique, it is important to determine the power splitting ratio at each antenna to balance the rate-energy trade-off between the information decoding (ID) and energy harvesting (EH) receivers. Note that time-switching and power-splitting receiver can be regarded as a special and low-complexity realization of power-splitting receiver with only binary (0 or 1) power splitting ratio at each receiving antenna. They are implemented by different hardware circuits (time switcher versus power splitter) in practice [36].

There are miscellaneous issues investigated by many researchers on wireless power transfer. A. M. Azman et al., investigated superimposition technique in wireless power transfer for enhancing the distance of transmission of the transmission coil [37]. This technique resulted in incrementation of the distance by up to 2 times compared to the system without superimposed technique. Yunfei Chen et al., investigated interference analysis in wireless power transfer [38]. They studied the co-channel interference (CCI) generated by wireless power transfer. They considered the effect on information delivery for three widely used setups of simultaneous wireless information and power transfer (SWIPT), hybrid access point (HAP) and power beacon (PB). In the book on Wireless Power Transfer edited by Johnson I. Agbinya, various innovative techniques for design of Optimal Wireless Power Transfer Systems are discussed [39]. The authors present new methods of delivering flux efficiently using the inductance-based transmitter to an inductance-based receiver by using either flux concentrator or separator. The flux coupling coefficient can be increased by the concentrator. This leads to increased flux delivered to the receiver by a large order of magnitude. Whereas the separator helps in reducing the crosstalk between two identical types of nodes and also leads to significant increase in power delivery. In another paper, Zhen Zhang et al., investigated energy encryption for wireless power transfer [40]. They studied the improved security performance of wirelessly transferred energy as an attempt to switch off other unauthorized energy transmission channels and enhancing security of energy transmission.

## 7. Conclusions

This chapter has presented brief outline of the state-of-the-art and developments in wireless power transfer using solar energy. The harvesting technologies of ambient solar radiation like solar photovoltaic, kinetic, thermal or electro-magnetic (EM) energy can be used to recharge the batteries and power various electronic gadgets. Brief on Radio frequency (RF) harvesting technologies is also presented. The energy converted to useful DC energy which can be used to charge electrical devices which need low power consumption. The chapter has also presented analysis of the parallel plate photovoltaic amplifier connected to a potentiometer as a Resistance-Capacitance (RC) circuit power amplifier. The effect of inductance and resulting power transfer was theoretically determined in the RC amplifier circuit. The electrical and thermal properties and measurements from a parallel plate photovoltaic amplifier were collected to analyze the unbalanced power transfer and inductance in a nonlinear RC circuit amplifier using equivalent transfer functions. The concept of Wireless Information and Power Transfer using Electromagnetic and Radio Waves of Solar Energy Spectrum is also briefly outlined. The chapter has also presented miscellaneous issues pertaining to wireless power transfer such as superimposition technique, interference, and security issues. Appendix has presented Equations for transmitter and receiver using mutual inductance of the magnetic resonance between transmitter and receiver.

## Appendix: Equations for design of a transmitter and a receiver

A transmitting antenna is surrounded by an electromagnetic field. This electromagnetic field is divided into two separate regions-the reactive near field and the radiating field. The energy is stored in the transmitting coil before it propagates as electromagnetic waves to the receiving coil [41].

The magnetic field experience between transmitter or receiver is called mutual inductance, which can be predicted through:

$$M = L_1 L_2 \quad (A1)$$

Where,  $L_1$  is inductance of transmitter coil and  $L_2$  is inductance of receiver coil. For circular loop coil the inductance can be calculated by using the following formula [42]:

$$L = N^2 \mu_o \mu_r \frac{D}{2} \left( \left( \ln \frac{8D}{d} \right) - 2 \right) \quad (A2)$$

Where

$N$  – Number of turns of the coil

$\mu = 4\pi \times 10^{-7}$  permeability of vacuum, (H/m)

$D$  – Diameter of loop coil (m).

$d$  – Diameter of conductor cross-section (m).

The coil inductance ( $L$ ) and optimal resonance frequency is determined based on operating frequency that has been used in the system, the capacitance  $C$  can be calculated by:



$$f_r = 1 / 2\pi (1 / \sqrt{LC}) \quad (A3)$$

Quality Factor,  $Q$  characterize the energy decay in an antenna coil which is inversely proportional with the energy loss in antenna coil before transfer to the receiving coil. The factor  $Q$  of coil can be determined using Quality factor:

$$Q = \omega L / (R_{ac} + R_{rad}) \quad (A4)$$

Where,  $R_{ac}$  is AC resistivity;  $R_{rad}$  is radiation resistivity. The quality factor  $Q$  can have values ranging from 0 to infinity. It is difficult to obtain the values of  $Q$  far above 1000 for antenna coils in actual practice [43]. A high- $Q$  antenna coil can be defined with  $Q$  greater than 100. These two coupling antenna coils should have  $Q$  greater than 100 for each of the coils for transmission of the energy wirelessly [44]. The efficiency of the transfer system is very low for the antenna coils which have  $Q$  between 100 and 200 [45]. For obtaining a high efficiency of the wireless power transfer system, a high factor  $Q$  which approximates to 1000 is preferred for design purposes [46].

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