ANALYSIS OF WIRELESS POWER TRANSFER

BY

NUAN SHUAIBU ISA

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DEDICATION

This work is dedicated first and foremost to God almighty, to my mom Mrs. Susan Nuan, my siblings and all who have been of great support.

DECLERATION

I, Nuan Shuaibu Isa, declare that this work was done by me and has never been presented elsewhere for the award of a degree. I also hereby relinquish the copyright to the Federal University of Technology Minna.

12/11/10
....
Nuan Shuaibu Isa
Student

3/11/2010
....
Mr. Enesi Yahaya
Supervisor

(Jan. 11, 2011)
....
Engr. A.G. Raji
Head of Department

1/12/10
....
External Supervisor
Engr. Dr. G. I. Ighalo

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ABSTRACT

As the earth's population continues to grow, the demand for electricity could outpace the ability to produce it and move it around. Transmission of power over long distances, across difficult terrain and under environmentally unfavorable conditions has been capital intensive, dangerous and a source of power loss to energy generation and transmission through the use of cables. For these reasons, scientists have tried to develop methods of wireless power transmission that will lead to clean sources of energy.

Wireless power transmission involves the transmission of electrical energy from generation point to the consumer end without any physical connection between them. This project analyses the possibility of power transfer over a distance of 2m via strongly coupled magnetic resonances provided they are at midrange distances and are strongly coupled.

TABLE OF CONTENTS

Dedication......i

Declaration......ii

Acknowledgement......iii

Abstract......iv

Chapter one - introduction

1.1 Preamble......1

1.2 Objectives......3

1.3 Scope of study......3

1.4 Motivation......3

1.5 Merits of wireless power transmission (WPT)......3

Chapter two - literature review

2.1 The need for energy and its transmission......6

2.2 Brief research history in relation to WPT...... 7

2.3 Historic modification of Maxwell's laws......8

2.4 Milestones in wireless power transfer......9

2.5 Tesla coil......10

2.6 The Schumann cavity......12

2.7 Definition of terms used...... 12

2.8 Modern day researches in WPT......23

2.8.1 Microwave power transmission......23

2.8.2 The non Hertzian wave......26

2.8.3 WPT via strongly coupled magnetic resonances.....27

Chapter three - WPT between two capacitively conducting wire loops

3.1 Basic principle.....29

3.2 Coupled mode theory.....31

3.3 Theoretical model for self resonance.....32

3.4 Coupling factor..... 36

3.5 Figure of merit for power transfer..... 36

3.6 Quality factor..... 37

3.7 Power transferred from source to device..... 37

3.8 Efficiency of the power transfer scheme.....38

3.9 A theoretical model.....39

Chapter four

4.1 Discussion of results.....46

Chapter five

5.1 Conclusion.....49

5.2 Limitations.....49

5.3 Suggestions for further work..... 49

References.....50

Appendix 51

LIST OF FIGURES

Figure 2.1 Schematic diagram of a Tesla coil..10

Figure 2.2 Circuit diagram of a simple tesla coil..11

Figure 2.3 Magnetic flux between two coils...15

Figure 2.4 Mutual inductance between two coils...16

Figure 2.5 A transformer utilizes energy coupling...18

Figure 2.6 An antenna's near and far fields...19

Figure 2.7 Evanescent wave coupling...22

Figure 2.8 Block diagram of microwave wireless power transmission......................23

Figure 2.9 A microwave transfer scheme...25

Figure 2.10 according to the theory, one coil can send energy to another coil that is in range, as long as the coils have the same resonant frequency....................27

Figure 3.1 Two wire loops at resonance can exchange energy...............................29

Figure 3.2 Block diagram of the transfer scheme..31

Figure 3.3 A capacitively loaded conducting wire loop...33

Figure 4.1 Plot of coupling factor against distance between loop centers..................46

Figure 4.2 Plot of coupling to loss ratios against distance between loops...................47

Figure 4.3 Plot of efficiency against distance between loops.................................48

CHAPTER ONE

1.0 INTRODUCTION

1.1 PREAMBLE

Technological development has unfolded new faces in many facets of engineering and science. Man has broken the barrier of distance communication with the invention of the telephone. Added to this, technology has opened a space to enable data, video and sound transmission without physical cabling. Wireless data, video and sound transmission has sown a seed of possibility for transmission of power without cables. And to this end researchers have plunged into the quest of making transmission of power without cables a reality.

Wireless power transmission is the transmission of electricity without physical cables. The quest has brought big organizations such as the American space agency to invest both financial and mental resources towards remote powering of heavy space machinery. The siemen engineering and other independent agencies are also undertaking research.

Wireless power transmission can be implemented and realized by three basic methods;

1. Microwave power transmission
2. Strongly coupled magnetic resonances or electromagnetic induction
3. Transmission through space

Microwave power transmission

In the 1980s, Canada's Communications Research Centre created a small airplane that could run off power beamed from the Earth. The unmanned plane, called the Stationary

High Altitude Relay Platform (SHARP), was designed as a communications relay. Rather than flying from point to point, the SHARP could fly in circles two kilometers in diameter at an altitude of about 13 miles (21 kilometers). Most importantly, the aircraft could fly for months at a time.

The secret to the SHARP's long flight time was a large, ground-based microwave transmitter. The SHARP's circular flight path kept it in range of this transmitter. A large, disc-shaped rectifying antenna, or rectenna, just behind the plane's wings changed the microwave energy from the transmitter into direct-current (DC) electricity. Because of the microwaves' interaction with the rectenna, the SHARP had a constant power supply as long as it was in range of a functioning microwave array [1].

Through strongly coupled magnetic resonances

This project is centered on this method of wireless power transmission. Power can be transferred between two capacitively loaded coils or loops separated by a few meters provided they are at resonance. As long as both coils are out of range of one another, nothing will happen, since the fields around the coils aren't strong enough to affect much around them. Similarly, if the two coils resonate at different frequencies, nothing will happen. But if two resonating coils with the same frequency get within a few meters of each other, streams of energy move from the transmitting coil to the receiving coil. One coil can even send electricity to several receiving coils, as long as they all resonate at the same frequency. This is the non-radiative energy transfer since it involves stationary fields around the coils rather than fields that spread in all directions [2].

Transmission through space

The third method of transmitting power through space is the Tesla system of wireless power transmission in which a resonating cavity is activated with a high pulse wave which radiates EM waves from the cavity there by causing the ionized gas transfer EM wave.

1.2 PROJECT AIM

To show theoretically that useful power can be sent wirelessly up to a distance of 2 meters between two capacitively-loaded conducting-wire loops when strongly coupled.

1.3 SCOPE OF STUDY

The scope of this work is limited to analytical calculations that demonstrate the feasibility of wireless power transfer via strongly coupled magnetic resonances using two capacitively-loaded conducting-wire loops to achieve resonance.

1.4 MOTIVATION

The major reasons why this project was embarked upon are

1. The desire to see rural areas being involved in active production if power can be beamed to them wirelessly
2. The need for wireless power grids since right of way and scarce infrastructures are militating against the regular wired grids.

1.5 MERITS OFWIRELESS POWER TRANSMISSION (WPT)

Consumer electronics

- Automatic wireless charging of mobile electronics (phones, laptops, game controllers, etc.) in home, car, office, Wi-Fi hotspots while devices are in use and mobile.
- Direct wireless powering of stationary devices (flat screen TV's, digital picture frames, home theater accessories, wireless loud speakers, etc.) Eliminating expensive custom wiring, unsightly cables and "wall-wart" power supplies.
- Direct wireless powering of desktop PC peripherals: wireless mouse, keyboard, printer, speakers, display, etc eliminating disposable batteries and awkward cabling

Industrial

- Direct wireless power and communication interconnections across rotating and moving "joints" (robots, packaging machinery, assembly machinery, machine tools) eliminating costly and failure-prone wiring.
- Direct wireless power and communication interconnections at points of use in harsh environments (drilling, mining, underwater, etc.) Where it is impractical or impossible to run wires.
- Direct wireless power for wireless sensors and actuators, eliminating the need for expensive power wiring or battery replacement and disposal.

- Automatic wireless charging for mobile robots, automatic guided vehicles, cordless tools and instruments, eliminating complex docking mechanisms, and labor intensive manual recharging and battery replacement.

Transportation

- Automatic wireless charging for existing electric vehicle classes: golf carts, industrial vehicles.
- Automatic wireless charging for future hybrid and all-electric passenger and commercial vehicles, at home, in parking garages, at fleet etc.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 THE NEED FOR ENERGY AND ITS TRAMSMISSION

Energy is one of the world's most important needs. Man has derived energy from wood, built machines capable of exploring fossil fuels and the best of engineering minds steam energy from the electron which is the bedrock of electrical engineering. The world not only awaits an alternative energy source to fossil fuel but also the ease of energy distribution to end users.

The field of electrical power has seen various changes starting from hydroelectric power (HEP) generation to nuclear power generation and all this has relied on cables for transmission of power to the final users. As man expands in mental coast, new engineering capabilities are given birth to and the reality of wireless power transmission is a consequence of man's mental coast, quest and need for wireless grid systems. Before major breakthroughs in engineering are made they are ushered by thesis and anti-thesis.

So many scientists have worked tirelessly to ensure that wireless power transmission became a reality and not just a myth. Some of them like Marconi were called mad men and even taken to mental institutions when they spoke about the possibility of sending information through the air without any medium. But today the world is a global village thanks to these mad men. The thoughts of these men have also triggered other scientists like tesla to think even farther and research into the possibility of sending power wirelessly.

2.2 BRIEF RESEARCH HISTORY IN RELATION TO WIRELESS POWER TRANSMISSION.

Humans have known about the existence of electricity for thousands of years, but scientists did not make great progress understanding it till the late 1700. It was during this period that early scientists began understanding electricity and its consequences.The major events that were registered in wireless power transmission occurred in electromagnetism. André-Marie Ampere (1775-1836) formulated the law of electromagnetism (Ampere's law) that describes mathematically the magnetic force between two circuits.

Then came in the field the legendary figure, James Maxwell with the seminal mathematical synthesis of all the previous experimental work on electricity and magnetism. His main predictions were:

- That wave of electromagnetism should exist and be able to travel in any medium the hypothetical ether included.
- That their speed could be deduced from purely electrical measurements
- That given the close agreement between the speeds of light determined in kohlsrauch and Weber's experiment. And the speed predicted for Electromagnetic (EM) waves, light itself was an EM wave.

Maxwell's equations predicting the existence of electromagnetic radiation propagating at the speed of light were made public in 1865, in 1888 Hertz had demonstrated generation of electromagnetic waves and that their properties were similar to those of light.

2.3 HISTORIC MODIFICATION OF MAXWELL'S LAWS

In the 1860s James Clerk Maxwell combined electrical fields and magnetic fields into a common model and launched the present system of classical electrodynamics still being taught today, though in a more limited form. In his 1865 paper, Maxwell specifically lists his 20 equations and his 20 unknowns. His work was strongly contested because few of the three dozen electrical scientists on earth at that time were good in quaternion mathematics. Before he died in 1879 Maxwell himself had started rewriting his 1873 book for a second edition with simpler equations.

In the 1880s Oliver Heaviside, a brilliant but self-taught scientist who never attended university played a major role in converting (reducing) Maxwell's equations to what today is vector algebra. After Maxwell was deceased, heaviside detested potentials and stated that they should be "removed form the theory". The reduction work by Heaviside, Gibbs and hertz resulted in the modern four vector equations in some four unknowns. These are taught along with a further truncation by Lorentz in every university as "Maxwell's equations"[3].

They are in fact Heaviside's equations further truncated by Lorentz symmetrical reguaging. Before Lorentz reguaging, the Maxwell-Heaviside equations were still difficult to solve and analytical methods were often required. This posed a calculation nightmare back in the mid 1800s before the advent of modern computers and automated calculations. Today, numerical methods can be accommodated much more easily, using computers.

2.4 MILESTONES IN WIRELESS POWER TRANSFER

Despite the fact that almost every book mentions Marconi (1874-1937) as the inventor of radio, the only thing Marconi did seems to be nothing more than reproducing apparition Tesla (1856-1943) had registered years ago.

1830: Tesla carries his first experiments with frequency electric currents the first demonstration for wireless communication. In his articles and lectures Tesla describes his first radio apparatus in detail.

1895: Marconi presents a radio device in London, claiming it as his invention. However, the device is the same as what Tesla had already described in his articles. Later on Marconi will claim that he had not read Tesla's articles despite that they were translated in many languages very quickly.

1897: Fist patent registered by Nikola Tesla on radio communication. Patent No. 645576.

1898: Tesla constructs the first remotely controlled boat and demonstrates it in New York. He registers this invention under patent No. 613809.

1899: Tesla builds a large radio station in Colorado Springs, USA and starts his experiments.

1901: Tesla begins the construction of a huge radio station in wanderclyffe near New York. This station, Tesla's biggest dream would transmit electric signals and energy to the whole planet. It was never completed due to lack of financial means. The same year, Marconi's great triumph was in succeeding to receive signals transmitted across the Atlantic Ocean despite the general opinion that the curvature of the earth would limit the range of communication by electromagnetic waves. This sensational achievement was the start of the vast development of radio communication and broadcasting. The world was impressed, but did not learn that Marconi was only using Tesla's No 645576 (1897).

1917: In an article in "Electrical Experimenter" Testla announces a system to locate metallic objects through radio signal reflection. This is the beginning of the radar.

2.5 TESLA COIL

A Tesla coil is a type of resonant transformer circuit invented by Nikola Tesla around 1891. It is used to produce high voltage, relatively high current, high frequency alternating current electricity. Tesla experimented with a number of different configurations and they consist of two, or sometimes three, coupled resonant electric circuits. Tesla used these coils to conduct innovative experiments in electrical lighting, phosphorescence, x-ray generation, high frequency alternating current phenomena, electrotherapy, and the transmission of electrical energy without wires.

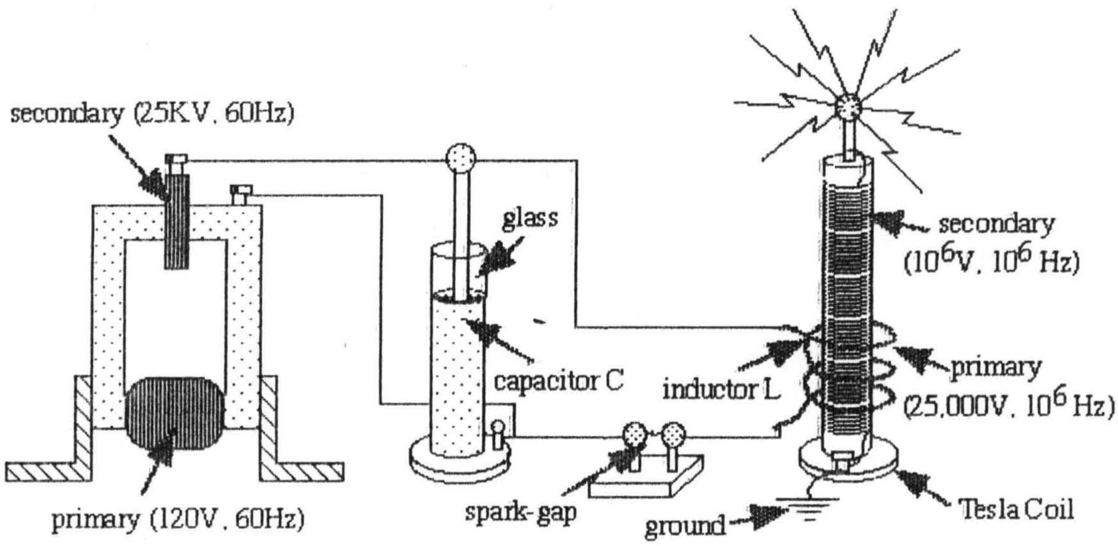

Fig 2.1 schematic diagram of a Tesla coil

The early Tesla coil transformer design employs a medium- to high-voltage power source, one or more high voltage capacitor(s), and a spark gap to excite a multiple-layer primary inductor with periodic bursts of high frequency current. The multiple-layer Tesla coil transformer secondary is excited by resonant inductive coupling, the primary and secondary circuits both being tuned so they resonate at the same frequency (typically, between 25 kHz and 2 MHz). The later and higher-power coil design has a single-layer primary and secondary. These Tesla coils are often used by hobbyists and at venues such as science museums to produce long sparks.

Tesla coil circuits were used commercially in spark gap radio transmitters for wireless telegraphy until the 1920's, and in electrotherapy and medical devices such as violet ray. (Although Tesla circuits were not the first or the only ones used in spark transmitters).

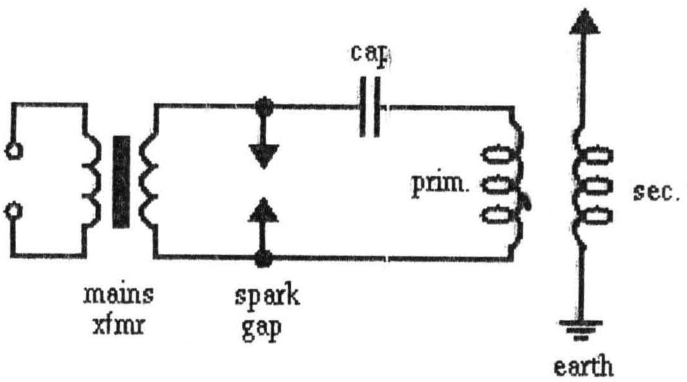

Fig 2.2 circuit diagram of a simple tesla coil

2.6 THE SCHUMANN CAVITY

Dr Tesla's approach was to build a cavity resonator which will be placed high above the earth surface and the base of the pole will be earthed. As the cavity resonator is exited the change activation in the atmosphere relative to the earth terminal will result in charge imbalance there by acting like a spherical resonator as a result the space will be able transmits current in wave like form.

Today it has been proven that electrical energy can be propagated around the world between the surface of the earth and the ionosphere at extreme low frequencies in what is known as the Schumann cavity. The Schumann cavity surrounds the earth between ground level and extends upward to a maximum 80 kilometers. Experiments to date have shown that electromagnetic waves of extreme low frequencies in the range of 8 Hz the fundamental Schumann Resonance frequency propagate with little attenuation around the planet within the Schumann cavity.

Knowing that a resonant cavity can be excited and that power can be delivered to that cavity similar to the methods used in microwave ovens for home use it should be possible to resonate and deliver power via the Schumann cavity to any point on earth this will result in practical wireless transmission of electrical power .

2.7 DEFINATION OF TERMS USED

Inductance

Inductance is the property in an electrical circuit where a change in the electric current through that circuit induces an electromotive force (EMF) that opposes the change in current.

In electrical circuits, any electric current, i, produces a magnetic field and hence generates a total magnetic flux, Φ, acting on the circuit. This magnetic flux, due to Lenz's law, tends to act to oppose changes in the flux by generating a voltage (a back EMF) in the circuit that counters or tends to reduce the rate of change in the current. The ratio of the magnetic flux times turns of wire to the current is called the self-inductance, which is usually simply referred to as the inductance of the circuit. To add inductance to a circuit, electronic components called inductors are used, which consist of coils of wire to concentrate the magnetic field.

The term 'inductance' was coined by Oliver Heaviside in February 1886. It is customary to use the symbol *L* for inductance, possibly in honor of the physicist Heinrich Lenz.

The SI unit of inductance is the henry (H), named after American scientist and magnetic researcher Joseph Henry. 1 H = 1 Wb/A.

The quantitative definition of the (self-) inductance of a wire loop in SI units (Webber's per ampere, known as henries) is

$$L = N\Phi / I \qquad (1.1)$$

where L is the inductance, Φ denotes the magnetic flux through the area spanned by the loop, N is the number of wire turns, and i is the current in amperes. The flux linkage thus is

$$N\Phi = L\, i. \qquad (1.2)$$

There may, however, be contributions from other circuits. Consider for example two circuits K_1, K_2, carrying the currents i_1, i_2. The flux linkages of K_1 and K_2 are given by

$$N_1\Phi_1 = L_{11}\, i_1 + L_{12}\, i_2 \qquad (1.3)$$

$$N_2\Phi_2 = L_{21}\, i_1 + L_{22}\, i_2 \qquad (1.4)$$

According to the above definition, L_{11} and L_{22} are the self-inductances of K_1 and K_2, respectively. It can be shown (see below) that the other two coefficients are equal: $L_{12} = L_{21} = M$, where M is called the mutual inductance of the pair of circuit [5].

Mutual inductance

An inductor generates an induced emf within itself as a result of the changing magnetic field around its own turns, and when this emf is induced in the same circuit in which the current is changing this effect is called Self-induction, (L). However, when the emf is induced into an adjacent coil situated within the same magnetic field, the emf is said to be induced magnetically, inductively or by Mutual-induction, symbol (M). Then when two or more coils are magnetically linked together by a common magnetic flux they are said to have the property of Mutual Inductance.

Mutual Inductance is the basic operating principal of transformers, motors, generators and any other electrical component that interacts with another's magnetic field. But mutual inductance can also be a bad thing as "stray" or "leakage" inductance from a coil can interfere with the operation of another adjacent component by means of electromagnetic induction, so some form of electrical screening to a ground potential is required.

The amount of mutual inductance that links one coil to another depends very much on the relative positioning of the two coils. If one coil is positioned next to the other coil so that their physical distance apart is small, then nearly nearly all of the magnetic flux from the first coil will interact with the turns of the second coil inducing a large emf and therefore producing a large mutual inductance value. Likewise, if the two coils are farther apart from each other the amount of induced magnetic flux from the first coil will be weaker producing a much smaller induced emf and therefore a much smaller mutual inductance value. So the effect of mutual inductance is very much dependent upon the relative positions or spacing, (S) of the two coils and this is shown below.

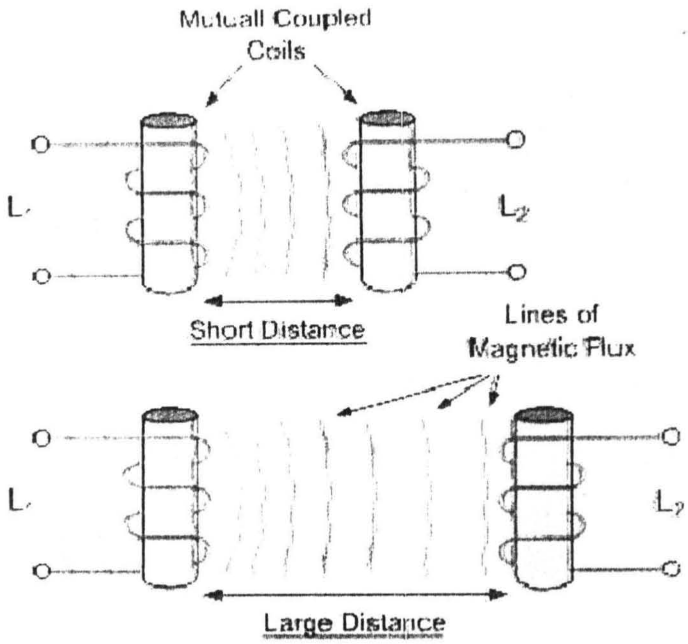

Fig 2.3 magnetic flux between two coils

The mutual inductance that exists between the two coils can be greatly increased by positioning them on a common soft iron core or by increasing the number of turns of either coil as would be found in a transformer. If the two coils are tightly wound one on top of the other over a common soft iron core unity coupling is said to exist between them as any losses due to the leakage of flux will be extremely small. Then assuming a perfect flux linkage between the two coils the mutual inductance that exists between them can be given as.

$$M = \mu_0 \mu_r N_1 N_2 A / l \qquad (1.5)$$

Where:

μ_o is the permeability of free space ($4.\pi. \times 10^{-7}$), μ_r is the relative permeability of the soft iron core, N is in the number of coil turns, A is in the cross-sectional area in $m^2$and l is the coils length in meters.

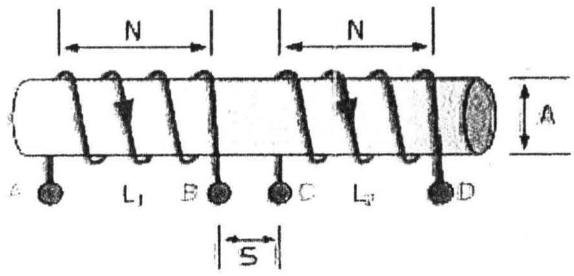

Fig 2.4 mutual inductance between two coils

from the law of Electromagnets, the self inductance of each individual coil is given as

$$L_1 = \mu_0 \, \mu_r N_1^2 A / l \qquad (1.6)$$

$$L_2 = \mu_0 \, \mu_r N_2^2 A / l \qquad (1.7)$$

Then by cross-multiplying the two equations above, the mutual inductance that exists between the two coils can be expressed in terms of the self inductance of each coil.

$$M^2 = L_1 \, L_2 \qquad (1.8)$$

giving us a final and more common expression for the mutual inductance between two coils as:

$$M = \sqrt{(L_1 \, L_2)} \text{ H} \qquad (1.9)$$

However, the above equation assumes zero flux leakage and 100% magnetic coupling between the two coils, L_1 and L_2. In reality there will always be some loss due to leakage and position, so the magnetic coupling between the coils can never reach or exceed 100%, but can become very close to this value in some special inductive coils. If some of the total magnetic flux links with the two coils, this amount of flux linkage can be defined as a fraction of the total possible flux linkage between the coils. This fractional value is called the Coefficient of Coupling and is given the letter k. Generally, the amount of inductive coupling that exists between the two coils is expressed as a fractional number between 0 and 1 instead of a percentage (%) value, were 0 indicates zero or no inductive coupling and 1 indicates full or maximum inductive coupling. Then the equation above which assumes unity coupling can be modified to take into account this coefficient of coupling, k and is given as:

$$K = M / \sqrt{(L_1 L_2)} \tag{1.10}$$

When the coefficient of coupling, k is equal to 1, (unity) such that all the lines of flux of one coil cuts all of the turns of the other, the mutual inductance is equal to the geometric mean of the two individual inductances of the coils. So when the two inductances are equal and L_1 is equal to L_2, the mutual inductance that exists between the two coils can be defined as [6]:

$$M = \sqrt{(L_1 L_2)} = L \tag{1.11}$$

Energy coupling

Energy coupling occurs when an energy source has a means of transferring energy to another object. One simple example is a locomotive pulling a train car the mechanical coupling between the two enables the locomotive to pull the train, and overcome the forces of friction and inertia that keep the train still and, the train moves. Magnetic coupling occurs when the magnetic field of one object interacts with a second object and induces an electric current in or on that object. In this way, electric energy can be transferred from a power source to a powered device. In contrast to the example of mechanical coupling given for the train, magnetic coupling does not require any physical contact between the object generating the energy and the object receiving or capturing that energy.

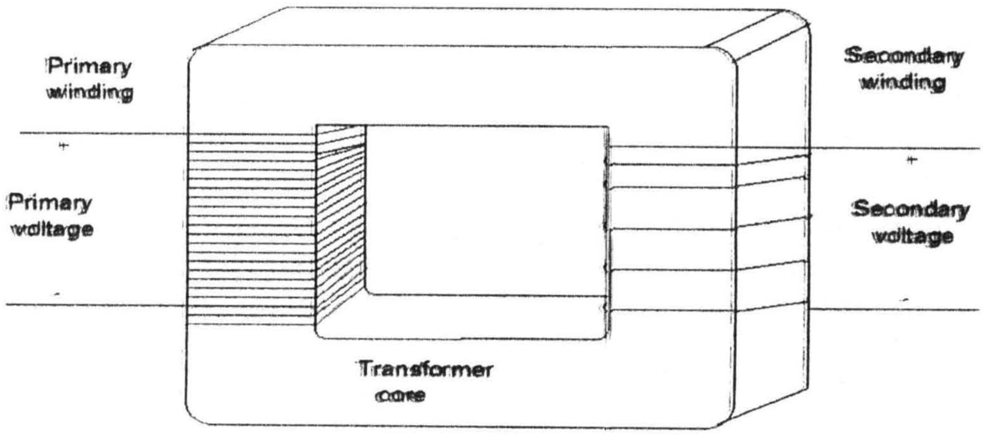

Fig 2.5 a transformer utilizes energy coupling

Resonance

Resonance is a property that exists in many different physical systems. It can be thought of as the natural frequency at which energy can most efficiently be added to an oscillating system. A playground swing is an example of an oscillating system involving potential energy and kinetic energy. The child swings back and forth at a rate that is determined by the length of the swing. The child can make the swing go higher if she properly coordinates her arm and leg action with the motion of the swing. The swing is oscillating at its resonant frequency and the simple movements of the child efficiently transfer energy to the system. Another example of resonance is the way in which a singer can shatter a wine glass by singing a single loud, clear note. In this example, the wine glass is the resonant oscillating system. Sound waves traveling through the air are captured by the glass, and the sound energy is converted to mechanical vibrations of the glass itself. When the singer hits the note that matches the resonant frequency of the glass, the glass absorbs energy, begins vibrating, and can eventually even shatter. The resonant frequency of the glass depends on the size, shape, thickness of the glass, and how much wine is in it [7].

Near and Far fields

The Near field and Far field, along with the Transition zone are boundary regions of the electromagnetic radiation that emanate from an antenna. Certain behavioral characteristics of electromagnetic fields dominate at one distance from the radiating antenna, while a completely different behavior can dominate at another location. Therefore, defined boundary regions categorize behavior characteristics of electromagnetic fields as a function of distance from the radiating source. The regional boundaries are usually measured as a function of the wavelength. The image on the next page shows these regions and boundaries.

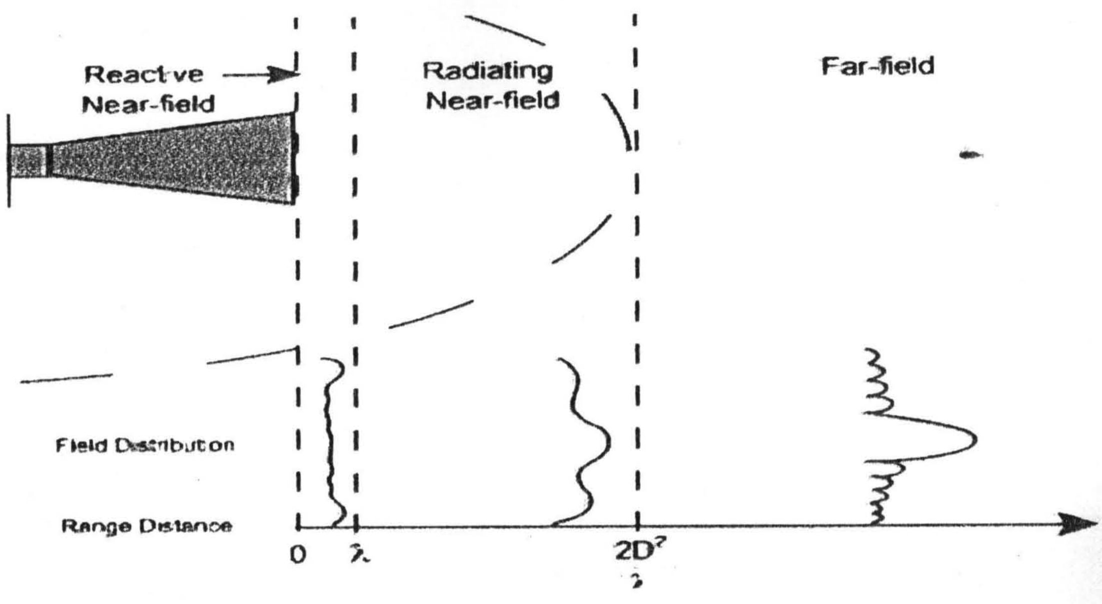

Fig 2.6 an antenna's near and far fields

It is worthy of note that these regions categorize behaviors which vary even within each region; and the boundaries for these regions are approximate "rules of thumb", as there are no precise cutoffs between boundaries. More precise boundaries can be defined in some cases, based primarily on antenna type and antenna size, but even in such cases, experts may differ on nomenclature. These terms are generally used in antenna measurements, but can also define the capabilities of novel or improved electromagnetic devices undergoing research. Hence, the region extending farther than 2 wavelengths away from the source is called the Far-Field. The region between the near-field and the far-field is called the Transition Zone, which has a combination of the characteristics found in both the near-field and the far-field.

The region located less than one wavelength from the source is called the Near-field. Any electromagnetic radiation consists of an electric field component E and a magnetic field component H. In the far-field, the relationship between the electric field component E and the magnetic component H is that characteristic of any freely propagating wave, where (in units where c = 1) E is equal to H at any point in space. By contrast, in the near-field, the relationship between E and H becomes very complex. Also, unlike the far-field where electromagnetic waves are usually characterized by a single polarization type (horizontal, vertical, circular, or elliptical), all four polarization types can be present in the near-field.

The near-field itself is further divided into the reactive near-field and the radiative near-field. The "reactive" and "radiative" near field designations are also a function of wavelength (or distance). However, these boundary regions are a fraction of one wavelength within the near-field. The outer boundary of the reactive near-field region is commonly considered to be a distance of $1/2\pi$ times the wavelength ($\lambda/2\pi$ or $0.159 \times \lambda$) from the antenna surface. The radiative near-field covers the remainder of the near-field region, from $\lambda/2\pi$ out to λ (one full wavelength) [8].

Evanescent wave

An evanescent wave is a near field standing wave with an intensity that exhibits exponential decay with distance from the boundary at which the wave was formed. Evanescent waves are a general property of wave-equations, and can in principle occur in any context to which a wave-equation applies. They are formed at the boundary between two media with different wave motion properties, and are most intense within one-third of a wavelength from the surface of formation. In particular, evanescent waves can occur in the contexts of: optics and other forms of electromagnetic radiation, acoustics, quantum mechanics, and "waves on strings" Evanescent wave coupling.

Evanescent wave coupling

In optics, evanescent wave coupling is a process by which electromagnetic waves are transmitted from one medium to another by means of the evanescent exponentially decaying electromagnetic field.Coupling is usually accomplished by placing two or more electromagnetic elements such as optical waveguides close together so that the evanescent field generated by one element does not decay much before it reaches the other element. With waveguides, if the receiving waveguide can support modes of the appropriate frequency, the evanescent field gives rise to propagating wave modes, thereby connecting (or coupling) the wave from one waveguide to the next.

Evanescent wave coupling is fundamentally identical to near field interaction in electromagnetic field theory. Depending on the impedance of the radiating source element, the evanescent wave is either predominantly electric (capacitive) or magnetic (inductive), unlike in the far field where these components of the wave eventually reach the ratio of the impedance of free space and the wave propagates radiatively. The evanescent wave coupling takes place in the non-radiative field near each medium and as such is always associated with matter, i.e. with the induced currents and charges within a partially reflecting surface. This coupling is directly analogous to the coupling between the primary and secondary coils of a transformer, or between the two plates of a capacitor. Mathematically, the process is the same as that of quantum tunneling, except with electromagnetic waves instead of quantum-mechanical wave functions [9].

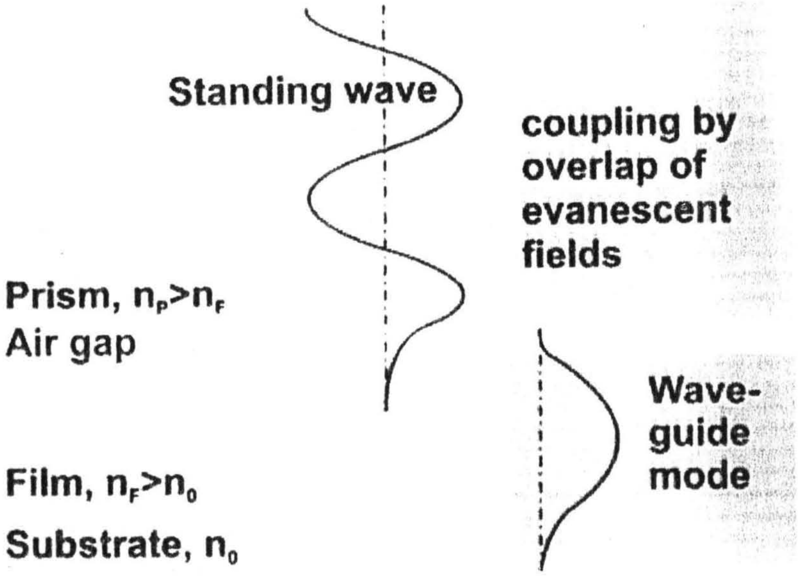

Fig 2.7 evanescent wave coupling

2.8 MODERN DAY RESEARCHES IN WPT

2.8.1 MICROWAVE POWER TRANSMISSION

Rectifying antennae are central to many wireless power transmission theories especially those using microwaves. They are usually made from an array of dipole antennae, which have positive and negative poles. These antennae connect to semiconductor diodes. Here's what happens:

1. Microwaves, which are part of the electromagnetic spectrum, reach the dipole antennae.
2. The antennae collect the microwave energy and transmit it to the diodes.
3. The diodes act like switches that are open or closed as well as turnstiles that let electrons flow in only one direction. They direct the electrons to the rectenna's circuitry.

4. The circuitry routes the electrons to the parts and systems that need them.

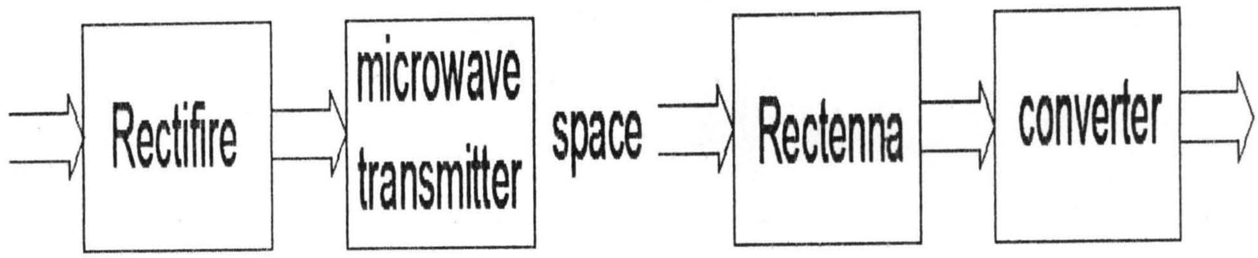

Fig 2.8 block diagram of microwave wireless power transmission

Other, longer-range power transmission ideas also rely on rectennae. David Criswell of the University of Houston has proposed the use of microwaves to transmit electricity to Earth from solar power stations on the moon. Tens of thousands of receivers on Earth would capture this energy, and rectennae would convert it to electricity. The idea behind long range microwave power transmission is that solar power satellite (SPS) consisting of panels of solar cells stretching many square kilometers in space converts the electricity gotten from light into radio waves and beam them wirelessly to the earth. If the largest conceivable space power station was built and operated 24 hours a day all year round, it could produce the equivalent output of ten million kilowatt-class nuclear power station which is rather impressive and in 1983, a Japanese team succeeded in a first ever experiment to transmit microwave energy through the ionosphere using two rockets.

In 1995 a team led by Prof. Nobuyuki Kaya of Kobe University managed to transmit electricity from the ground to an airship in the sky. Japanese scientists say that if microwaves carrying electric power can be headed uniformly over the earth they could be used as a power for mobile devices such as cell phones. The power of microwaves would have to be weaker than the regulatory standard to prevent any physical harm to people from the electromagnetic rays. The mobile phone now in use require up to approximately 800mW of power. To receive microwave energy, they would need an antenna about 25-30cm square. As it would not be feasible for a mobile handset to itself serve as the antenna the options would be to reduce the power consumption or devise a large antenna [1].

Microwaves pass through the atmosphere easily, and rectenna rectify microwaves into electricity very efficiently. In addition, Earth-based rectenna's could be constructed with a mesh-like framework, allowing the sun and rain to reach the ground underneath and minimizing the environmental impact. Such a setup could provide a clean source of power. However, it does have some drawbacks:

- The solar power stations on the moon would require supervision and maintenance. In other words, the project would require sustainable, manned moon bases.
- Only part of the earth has a direct line of sight to the moon at any given time. To make sure the whole planet had a steady power supply, a network of sate would have to re-direct the microwave energy.
- Many people would resist the idea of being constantly bathed in microwaves from space, even if the risk were relatively low.
- The fundamentals are already in place, but the Japanese say that another problem with microwave power transmission is the exorbitant cost of constructing an SPS around 2.4 trillion yen in total as a rough estimate.

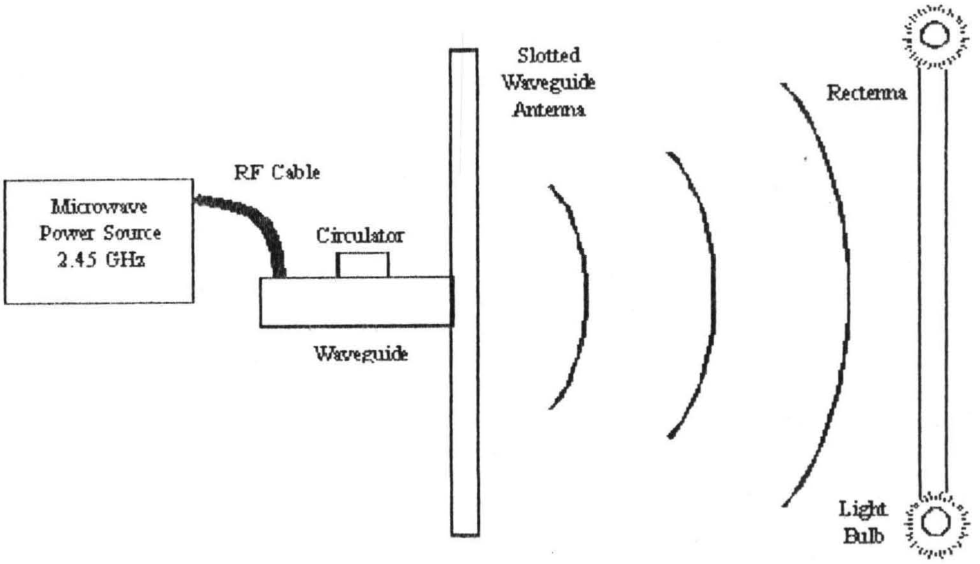

Fig 2.9 A microwave transfer scheme

2.8.2 NON HERTZIAN WAVE

The term non-hertzian wave was used in relation to the Colorado spring experiment in which Tesla experimented on his systems for wireless power transmission. Amongst present day researcher Col. Tom Bearden has pioneered a lot of research to unveil what Dr Tesla meant by the term non-hertzian wave in the course of his research given birth to what is refer to as motionless electromagnetic generator (MEG) which he claims uses energy from the vacuum. The fundamental principle upon which the MEG and wireless power manumission work is on the controversial longitudinal electromagnetic scalar wave.

March 26 2002 recorded a silent history a day which the motionless electromagnetic generator was patent with US patent agency. As we speak there is subscription for the product online at www.chenetic.org. The MEG was a proof to other researchers that what Tesla meant by non-hertzian was actually longitudinal electromagnetic scalar wave [4]. Another researcher justifying the existence of longitudinal lector magnetic scalar wave is Prof. C. Meyl who complain on the application in relation to warmed and the like the disasters when fashion into warhead.

2.8.3 POWER TRANSFER VIA STRONGLY COUPLED MAGNETIC RESONANCES

The past decade has witnessed a surge in the use of autonomous electronic devices (laptops, cell phones, robots, PDAs, etc.). As a consequence, interest in wireless power has reemerged .Radioactive transfer, although perfectly suitable for transferring information, poses a number of difficulties for power transfer applications. The efficiency of power transfer is very low if the radiation is omni directional and unidirectional radiation requires an uninterrupted line of sight and sophisticated tracking mechanisms.

In November 2006, however, researchers at MIT reported that they had discovered an efficient way to transfer power between coils separated by a few meters. The team, led by Marin Soljacic, theorized that they could extend the distance between the coils by adding resonance to the equation. Intuitively, two resonant objects of the same resonant frequency tend to exchange energy efficiently, while dissipating relatively little energy in extraneous offset resonant objects. In systems of coupled resonances (e.g., acoustic, electromagnetic, magnetic, nuclear), there is often a general "strongly coupled" regime of operation. 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 [2].

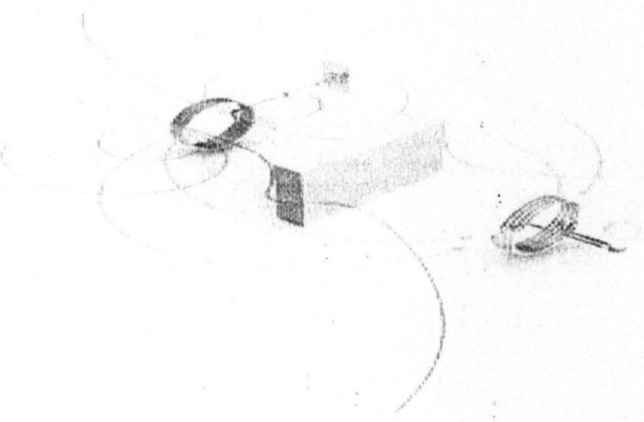

Fig2.10 according to the theory, one coil can send energy to another coil that is in range, as long as the coils have the same resonant frequency.

The above considerations apply irrespective of the physical nature of the resonances. Here, focus is laid on one particular physical embodiment magnetic resonances. Magnetic resonances are particularly suitable for everyday applications because most of the common materials do not interact with magnetic fields, so interactions with environmental objects are suppressed even further. We were able to identify the strongly coupled regime in the system of two coupled magnetic resonances by exploring nonradiative (near-field) magnetic resonant induction at megahertz frequencies. At first glance, such power transfer is reminiscent of the usual magnetic induction; however, note that the usual non resonant induction is very inefficient for midrange applications.

CHAPTER THREE

3.0 WIRELESS POWER BETWEEN TWO CAPACITIVELY LOADED CONDUCTING WIRE LOOPS

3.1 BASIC PRINCIPLE

Magnetic coupling occurs when two objects exchange energy through their varying or oscillating magnetic fields. Resonant coupling occurs when the natural frequencies of the two objects are approximately the same.

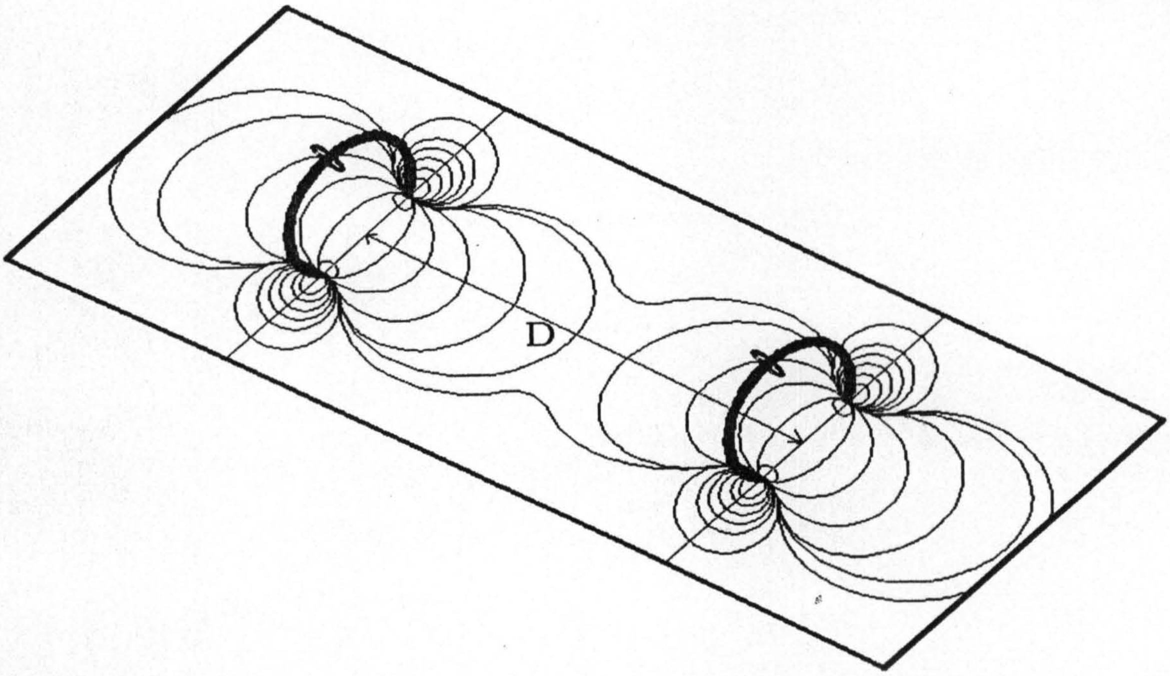

Fig 3.1 two wire loops at resonance can exchange energy

Basically, 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 resonances (e.g., acoustic, electromagnetic, magnetic, nuclear), there is often a general "strongly coupled" regime of operation [13]. 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 omnidirectional and efficient, irrespective of the geometry of the surrounding space, with low interference and losses into environmental objects.

The basic principle behind this system is that, if two resonant circuits are tuned at same frequency then their near fields (consisting of evanescent waves coupled by means of evanescent wave coupling) due to evanescent wave coupling standing wave developed between the inductors will allow energy to transfer from one object to another with time. Evanescent wave coupling is a process by which electromagnetic waves are transmitted from one medium to another by means of evanescent exponentially decaying electromagnetic field. The reason behind the use of non-radiative transfer scheme for this system is that in the case of non-radiative objects when energy is applied, it remains bound to them, rather than escaping to space. If you bring another resonant object with same frequency close enough to this 'tails' then energy can tunnel from one to the other object.

Magnetic resonances are particularly suitable for everyday applications because most of the common materials do not interact with magnetic fields, so interactions with environmental objects are suppressed even further. The strongly coupled regime in the system of two coupled magnetic resonances is identified by exploring non radiative (near-field) magnetic resonant induction at megahertz frequencies. At first glance, such power transfer is reminiscent of the usual magnetic induction; however, note that the usual non resonant induction is very inefficient for midrange applications. Midrange application means that the sizes of the devices that participate in the power transfer are smaller than the distance between devices by a factor of at least 2 to 3. For example, if the device being powered is a laptop (size ~50 cm) and the power source (size ~50 cm) is in the same room as the laptop, the distance of power transfer should be greater than a meter.

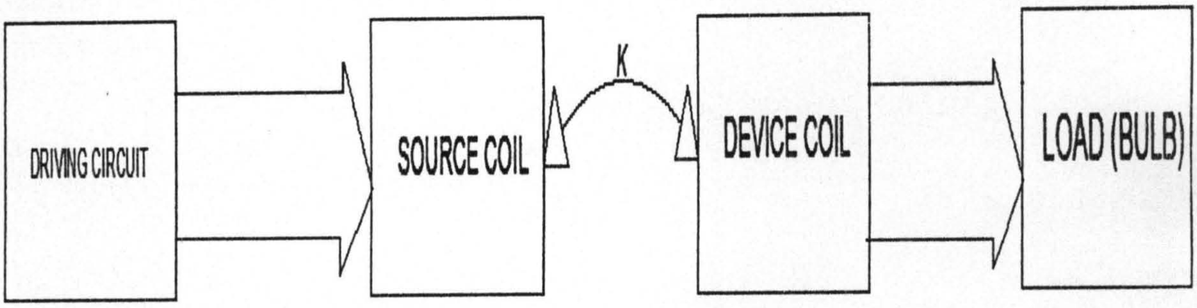

Fig 3.2 block diagram of the transfer scheme

3.2 THE COUPLED MODE THEORY

In order to achieve Efficient Power transfer there are some ways used for tuning parameters of given system so that it is operated in strongly coupled regime. Coupled Mode Theory (CMT) provides a simple and accurate way of modeling the system and gives more understanding of what makes power transfer efficient in a strongly coupled regime [10]. According to CMT when two resonators m and n have equal frequencies ($\omega_m = \omega_n$) then, when resonator m is excited at t = 0 and $a_m = 1$ and resonator n is unexcited i.e. $a_n = 0$, then phases of two solutions evolve at different rate, and after time $t = \pi/2k$ all of excitation will be transferred to the other resonator. The field is given as

$$F(r, t) = a_m(t)F_m(r) + a_n(t)F_n(r) \qquad (2.1)$$

Where,

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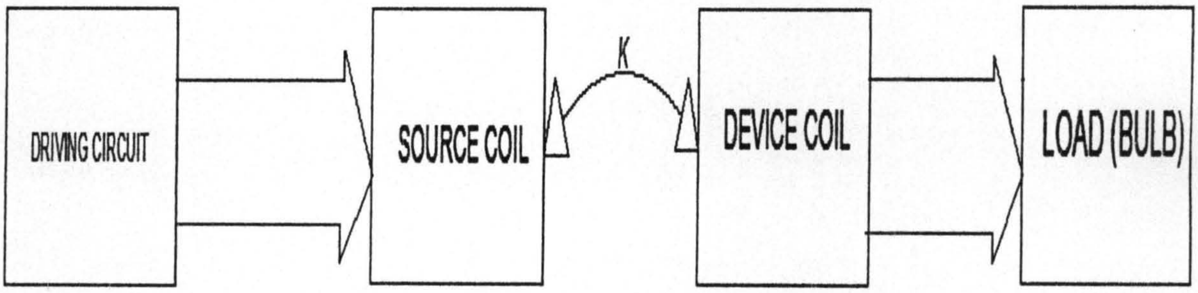

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$$F(r, t) = a_m(t)F_m(r) + a_n(t)F_n(r) \tag{2.1}$$

Where,

$F_m(r)$ and $F_n(r)$ are the Eigen modes of m and n alone,

and $a_m(t)$ and $a_n(t)$ are the field amplitudes and can be shown to satisfy, to lowest order:

$$da_m/dt = -i(\omega_m - i\Gamma_m)a_m + i\kappa a_m \tag{2.2}$$

$$da_n/dt = -i(\omega_n - i\Gamma n)a_n + i\kappa a_n \tag{2.3}$$

where ,

ω_m and ω_n are the individual Eigen frequencies,

Γ_m and Γ_n are intrinsic decay rates in the two objects due to absorption and radiation losses, and κ is the coupling coefficient.

Eqs. (2) and (3) show that at exact resonance ($\omega_m = \omega_n$ and $\Gamma_m = \Gamma_n$), the normal modes of the combined system are split by 2κ ,the energy exchange between the two objects takes place in time $\sim \pi/2\kappa$ and is nearly perfect, apart for losses, which are minimal when the coupling rate is much faster than all loss rates i.e when $\kappa >> \Gamma_m$ and Γ_n

Limiting the treatment to the case of two objects, denoted by source and device, such that the source (identified by the subscript s) is driven externally at a constant frequency, and the two objects have a coupling coefficient k. Work is extracted from the device (subscript d) by means of a load (subscript work) that acts as a circuit resistance connected to the device, and has the effect of contributing an additional term Γ_w to the unloaded device object's decay rate Γ_d. The overall decay rate at the device is therefore

$$\Gamma'_d = \Gamma_d + \Gamma_{work}. \tag{2.4}$$

The work extracted is determined by the power dissipated in the load, that is,

$$2\,\Gamma_{work}\,|a_d(t)|^2 \tag{2.5}$$

3.3 THEORITICAL MODEL FOR SELF RESONACE

The theoretical realization of the scheme consists of two identical capacitively loaded conducting wire loops. One loop is called the source (denoted by s) which could be coupled inductively to an oscillating circuit to drive the whole transfer scheme; the other loop is called the device (denoted by d) which could be coupled to a load. Self resonant wire loops rely on the interplay between distributed inductance and distributed capacitance to achieve resonance. The wire loops are made of an electrically conducting wire (copper) of length (l) cross-sectional radius(a) and loop radius(r) connected to a pair of conducting parallel plates of area (A) spaced by a distance (d) via a dielectric permittivity (ε) and everything surrounded by air.

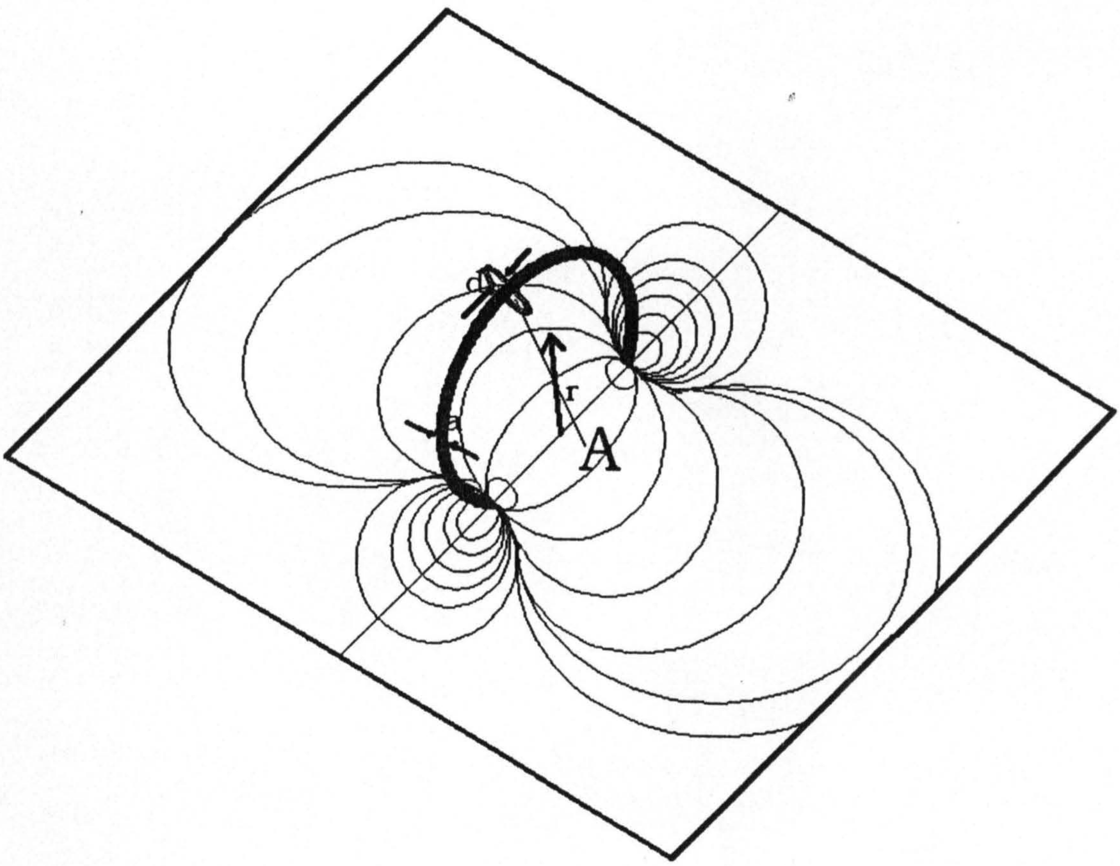

Fig 3.3 a capacitively loaded conducting wire loop

The current must be zero at the ends of the wire loop, and we make the educated guess that the resonant modes of the loop are well approximated by sinusoidal current profiles along the length of the conducting wire. We are interested in the lowest mode, so if we denote by s the parameterization coordinate along the length of the conductor, such that it runs from $-l/2$ to $+l/2$, then the time-dependent current profile has the form

$$I_0 \cos(\pi s/l) \exp(i\omega t) \tag{2.6}$$

It follows from the continuity equation for charge that the linear charge density profile is of the form

$$\lambda_0 \sin(\pi s/l) \exp(i\omega t) \tag{2.7}$$

So that one-half of the (when sliced perpendicularly to its axis) contains an oscillating total charge (of amplitude $q_0 = \lambda_0/\pi$) that is equal in magnitude but opposite in sign to the charge in the other half.As the coil is resonant, the current and charge density profiles are $\pi/2$ out of phase from each other, meaning that the real part of one is maximum when the real part of the other is zero. Equivalently, the energy contained in the coil is at certain points in time completely due to the current, and at other points it is completely due to the charge. Using electromagnetic theory, we can define an effective inductance [11] L and an effective capacitance C for each loop as follows:

$$L = \mu_0 r [\ln(8r/a)] - 2 \tag{2.8}$$

$$C = \varepsilon_0 \varepsilon A / d \tag{2.9}$$

Where μ_0 is the permeability of free space, ε_0 is the permittivity of free space and ε is the relative permittivity of the medium between the capacitance plates.

Given this relation and the equation of continuity, the resulting resonant frequency, f_o is

$$f_0 = 1/2\pi\sqrt{(LC)} \tag{2.10}$$

And

$$\omega = 2\,\pi\,f_0 \tag{2.11}$$

We can now treat this coil as a standard oscillator in coupled-mode theory by

Defining

$$a(t) = [\sqrt{(L/2)}]\; I_0\,(t) \tag{2.12}$$

We can estimate the power dissipated by noting that the sinusoidal profile of the current distribution implies that the spatial average of the peak current squared is

$$|I_0|^2 / 2 \tag{2.13}$$

For a wire loop made of a material with conductivity(σ), we modify the standard formulas for ohmic (R_{abs}) and radiation (R_{rad}) resistances accordingly [11]:

$$R_{abs} = \sqrt{(\mu_c \omega / 2\,\sigma)} \times (r / a) \tag{2.14}$$

Where μ_c is the complex permeability of of copper which takes skin effect into consideration [12]

$$R_{rad} = \pi/6 \times n_0\,(r/\lambda)^4 \;\; [11] \tag{2.15}$$

Where λ is the wavelength and η_0 is the characteristic impedance given by

$$n_0 = \sqrt{(\,\mu_0/\,\varepsilon_0\,)} \tag{2.16}$$

The coupled-mode theory decay constants for the loops are therefore

$$\Gamma^{rad} = R_{rad}\,/2L \tag{2.17}$$

And

$$\Gamma^{abs} = R_{abs}\,/2L \tag{2.18}$$

Thus the total decay constants for the source and the device are

$$\Gamma_s = \Gamma_d = \Gamma = \Gamma^{rad} + \Gamma^{abs} \tag{2.19}$$

3.4 COUPLING FACTOR (k)

The coupling factor k is the factor that determines the strength of interaction between the source and device fields. If this factor is greater than one (k >> 1) then system is strongly coupled else if it is less than one (k << 1), then the system is said to be weakly coupled.

From the coupled mode theory,

$$\kappa = \omega M / 2(L_s L_d)^{1/2} \tag{2.20}$$

Where M is the effective mutual inductance given as

$$M = [(\pi/2)\mu_0 \times (r_1 r_2)^2] / D^3 \tag{2.21}$$

When the distance D between the centers of the coils is much larger than their Characteristic size, κ scales with the D^{-3} dependence characteristic of dipole-dipole coupling. Both κ and Γ are functions of the frequency, and κ/ Γ and the efficiency is maximized for a particular value of f, which is in the range 1 to 50 MHz for typical parameters of interest. Thus, picking an appropriate frequency for a given coil size, plays a major role in optimizing the power transfer.

3.5 FIGURE OF MERIT FOR POWER TRANSFER

A wireless power system is limited by the power losses which appear in the system. This is wasted energy and the losses generate heat, which sets an upper limit of power which can be transferred. Therefore, an optimization strategy aims in minimizing the losses.

The losses can be expressed as loss factor

$$\lambda = P_{loss}/P_{out} \tag{2.22}$$

Which is the sum of all losses related to the transferred power, A deeper analysis results in a minimum loss factor, which can be achieved by a given wireless power system, if it is properly matched to load and generator.

This minimal loss factor can be achieved if the coupling occurs faster than all the losses (i.e $\kappa >> \Gamma_s \Gamma_d$), it is this ratio of coupling factor to the losses that will be set as the figure-of-merit for any system under consideration for wireless energy-transfer, along with the distance over which this ratio can be achieved,

I.e figure-of-merit (F.O.M) $\sim \kappa / \sqrt{\Gamma_s \Gamma_d}$ (2.23)

3.6 QUALITY FACTOR (Q)

The quality factor Q is used to determine the rate at which energy is lost from the system. The voltage, which is induced by the same current in an inductor scales with the frequency *f* and thus the apparent power in the device. The general definition of the quality factor is based on the ratio of apparent power to the power losses in a device. From this definition, the quality factor of a coil results to:

$Q = P_{app}/$ losses (2.24)

i.e $Q = \omega/2\Gamma$ (2.25)

Where radiative loss, $\Gamma = (R_{sbs} + R_{rad}) / 2L$

In one period of oscillation the resonant object loses 1/Q of its energy .The quality factor *Q* can have a value between 0 and infinity. But technically it is difficult to obtain values far above 1000 for coils. For mass production you may expect values around 100. A quality factor below 10 is not very useful. These values have to be considered as the typical order of magnitude. The quality factor *Q* is in first order only dependent on the shape and size of the coil and on the used materials for a fixed operating frequency. For typical technologies (e.g. wire-wound coils, PCB coils) typical quality factors can be given.

3.7 POWER TRANSFERRED FROM SOURCE TO DEVICE (P_{work})

From the coupled mode theory, different temporal schemes can be used to estimate the power extracted from the source to the device. In this project, a steady-state solution is assumed in which currents and charge densities vary in time as exp (iωt). Thus, the field amplitudes inside the source is maintained constant and given as

$$a_s(t) = A_s e^{(-jwt)} \tag{2.26}$$

and that in the device is

$$a_d(t) = A_d e^{(-jwt)} \tag{2.27}$$

with

$$A_d / A_s = k / (\Gamma + \Gamma_{work}) \tag{2.28}$$

And

$$\Gamma_{work} / \Gamma = \sqrt{(1 + F.O.M^2)} \tag{2.29}$$

The useful power extracted for work from the driving circuit is

$$P_{work} = 2\,\Gamma_{work}\,|A_d|^2 \quad (\text{from } p = i^2R) \tag{2.30}$$

Radiated or scattered power is

$$P_{rad} = 2\,\Gamma_s^{rad}\,|A_s|^2 + 2\,\Gamma_d^{rad}\,|A_d|^2 \tag{2.31}$$

Power absorbed at the source is

$$P_s = 2\,\Gamma_s^{abs}\,|A_s|^2 \tag{2.32}$$

Power absorbed at the device is

$$P_d = 2\,\Gamma_d^{abs}\,|A_d|^2 \tag{2.33}$$

3.8 EFFICIENCY OF THE POWER TRANSFER SCHEME (n)

From energy conservation, total time power entering the system is

$$P_{total} = P_{work} + P_{rad} + P_s + P_d \qquad (2.34)$$

Hence, efficiency is

$$n = P_{work} / P_{total} \qquad (2.35)$$

Maximizing the efficiency η of the transfer with respect to the loading Γ_{work} is equivalent to solving an impedance matching problem. One finds that the scheme works best when the source and the device are resonant i.e ($\omega_s = \omega_d$ and $\Gamma_s = \Gamma_d$), in which case the efficiency is

$$n = \frac{\Gamma_{work}|a_d|^2}{\Gamma_s|a_s|^2 + (\Gamma_d+\Gamma_{work})\,|a_d|^2} \qquad (2.36)$$

$$= \frac{\dfrac{\Gamma_{work}}{\Gamma_d}\ \dfrac{\kappa^2}{\Gamma_d\Gamma_s}}{[1+\Gamma_{work}/\Gamma_d)\,\kappa^2/\Gamma_s\Gamma_d] + [(1+\Gamma_{work}/\Gamma_d)^2]\ ]} \qquad (2.37)$$

For maximum efficiency, n_{max}

$$\Gamma_w/\Gamma_d = \sqrt{\ }\ [1+(\kappa^2/\Gamma_d\Gamma_s)] \qquad (2.38)$$

The efficiency is maximized when the rate of energy transfer between source and device is greater than rate of energy dissipation that is,

$k >> \Gamma_s \times \Gamma_d$ or

$$\kappa^2/\Gamma_d\Gamma_s > 1 \qquad (2.39)$$

where $\Gamma_s \times \Gamma_d$ is rate at which source and device are dissipating energy. If above condition is Satisfied then energy travels from source to device before too much gets wasted. This is commonly referred to as the "strong coupling Regime"[13].

3.9 A THEORITICAL DEMONSTRATION

Conditions for power transfer;

Considering all the factors described above, for any system to efficiently transfer power, it has to have the following requirements;

1. The sizes of the devices that will participate in the power transfer (r) should be smaller than the distance (D) between the devices by a factor of at least 2 to 3 i.e D/r range from 3 to 10.
2. The field maximized should be the non-lossy stationary near field and not the lossy far field.
3. Since the extent of the field into the air surrounding a finite sized object is determined by its wavelength, the scheme can be achieved by using objects of subwavelenght sizes i.e. the wavelength of the carried wave should be greater than the objects size which produces long evanescent field tails (i.e $\lambda >> r$ or $\lambda/r >> 1$
4. The coupling rate must be faster than the losses (i.e $k >> \Gamma_d \Gamma_s$ or $k / \Gamma >> 1$)
5. It should have a high quality factor for slow intrinsic loss rates

   (i.e $Q = \omega/2\Gamma > 1000$)

Loop parameters and calculations;

A system of two capacitively loaded conducting wire loops were used for the the theoretical demonstration, several sizes of loops and capacitance plates were tested, but the dimensions utilized that best satisfies the conditions for efficient power transfer up to a distance of 2 meters are given below;

Copper wires of cross-sectional area a = 2cm or 0.02m bent into a loop of radius r = 30cm loaded with two capacitance plates of area A = $138cm^2$ or $138 \times 10^{-4}\ m^2$ with distance between the plates d = 4mm or 0.004m separated by a material of permittivity $\varepsilon = 10$ and everything surrounded by air.

For copper, conductivity $\sigma = 5.9 \times 10^7$ m/ohms, complex permeability

$\mu_c = 1.35 \times 10^{-6}$ H/m with $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m and $\mu_0 = 4\pi \times 10^{-7}$ H/m

From these, the following can be determined;

From eq(2.8)

Inductance, $L = 4\pi \times 10^{-7} [\ \ln(8 \times 0.3 / 0.02) - 2\ ]$

$$L = 1.05 \times 10^{-6}\ H$$

From eq (2.9)

Capacitance, $C = (8.85 \times 10^{-12} \times 10 \times 138 \times 10^{-4}) / 0.004$

$$C = 3.05 \times 10^{-10}\ F$$

From eq (2.10),

Resonant frequency, $f_0 = 1 / \ [2\pi\ \sqrt{(3.05 \times 10^{-10} \times 1.05 \times 10^{-6})}\ ]$

$$f_0 = 8.88\ MHz$$

and $\omega = 2\pi \times 8.88MHz$

$$\omega = 55.84\ MHz$$

Now wavelength of the wave at resonance is

$\lambda = c / f_0$ (where c is the speed of light)

$\lambda = (3.01 \times 10^{8}) / (8.88 \times 10^{6})$

$\lambda = 33.65m$

from eq (2.14),

Absolute resistance, $R_{abs} = \sqrt{(\mu_c \omega / 2\sigma)} \times (r / a)$

$R_{abs} = \sqrt{[(1.35\times 10^{-6}\times 55.84 \times 10^{6}) / 2\times5.9\times10^{7}]} \times 0.3/0.002$

$R_{abs} = 0.01 ohms$

From eq (2.15),

Radiation resistance, $R_{rad} = \pi/6 \times n_0 (r/\lambda)^4$

But characteristic impedance, $n_0 = \sqrt{(\varepsilon_0 / \mu_0)}$

$n_0 = \sqrt{[8.85 \times 10^{-12} / 4\pi \times 10^{-7}]}$

$n_0 = 376.76$ ohms

Hence

$R_{rad} = \pi/6 \times 376.758 \times (0.3/33.65)^4$

$R_{rad} = 2.01 \times 10^{-3}$ ohms

Now the intrinsic losses are;

Radiation loss, $\Gamma^{rad} = R_{rad} / 2L$

$\Gamma^{rad} = 2.01 \times 10^{-3} / 2\times1.05\times 10^{-6}$

$\Gamma^{rad} = 958.09$

Absolute loss, $\Gamma^{abs} = R_{abs} / 2L$

$\Gamma^{abs} = 0.01 / 2\times1.05\times 10^{-6}$

$\Gamma^{abs} = 5{,}714.26$

Total intrinsic losses, $\Gamma = \Gamma^{abs} + \Gamma^{rad}$

$\Gamma = 5{,}714.26 + 958.09$

$\Gamma = 6{,}672.35$

Using the formula's for mutual inductance from eq (2.20)$M = [(\pi/2)\mu_0 \times (r_1 r_2)^2] / D^3$ to get the coupling factor $\kappa = \omega M / 2(L_s L_d)^{1/2}$ and quality factor $Q = \omega / 2\,\Gamma$, various values of coupling to loss ratios (k/Γ) and $\omega / 2k$ were estimated using a simple java program (see appendix A). These values were obtained for various distances D between the centers of the two coils with values of D ranging from 0.5m to 3m.

The results obtained are below;

Table 3.1 values obtained using the java program

Note last column is not in percentage. Multiply by 100 to convert.

D(m)	M(H)	K	Q	k/Γ	κ^2/Γ^2	ω / 2k	η
0.5	1.28013E-7	34039282.	4184.432	510.154	5.1584	8.202	0.99
1.0	1.28013E-7	4254910.0	4184.432	63.7692	8.0600	65.6183	0.96
1.5	4.74122E-9	126071.41	4184.432	18.8946	7.0760	221.461	0.90
2.0	2.00020E-9	53186.378	4184.432	7.97116	1.2593	524.946	0.79
2.5	1.02410E-9	27231.426	4184.432	4.08123	3.3014	1025.28	0.66
3.0	5.92653E-10	15758.927	4184.432	2.36183	1.1056	1771.69	0.52
3.5	3.73215E-10	9923.9890	4184.432	1.48733	4.3846	2813.38	0.38
4.0	2.50025E-10	6648.2973	4184.432	0.99640	1.9677	4199.57	0.26
4.5	1.75600E-10	4669.3117	4184.432	0.69980	9.7065	5979.46	0.16
5.0	1.28013E-10	3403.9282	4184.432	0.51015	5.1584	8202.28	0.10

Power transferred and efficiency calculations;

Now on trying to transfer 60watts of power to the load i.e $P_{work} = 60$ W if the source loop is fed with a 240v supply at the resonant frequency of 8.9MHz (this frequency could be generated by a collpitts oscillator which could serve as the driving circuit).

The total power at the device coil is;

$P = I V$

$I_d = P / v = 60 / 240 = 0.25A$

Assuming steady state solution, $I_d(t) = 0.25e^{jwt}$ A

For distance D = 2.1 m, k = 45,893.34 , FOM = 6.8 (table3.1) and $\Gamma_{work} = \Gamma_d \sqrt{(1+F.O.M^2)}$ (from eq 2.29)

$\Gamma_{work} = 6{,}672.35 \times \sqrt{(1+6.8^2)}$

$\Gamma_{work} = 45{,}859.97$

The amplitude of the field in the source is;

$A_s = 0.02927$

Assuming a steady state solution, this amplitude will be constant along the source loop and will at any time t be;

$a_s (t) = A_s e^{-jwt)}$ (from eq 2.26)

$a_s(t) = 0.02927e^{-iwt}$

The field amplitude in the device can be gotten from eq (2.28) which relates A_s and A_d given by;

$A_d / A_s = k / (\Gamma + \Gamma_{work})$

$A_d = A_s k / (\Gamma + \Gamma_{work})$

$A_d = (0.2927 \times 45{,}893.34) /(45{,}859.9697+6{,}672.35)$

$A_d = 0.02557$

and

$a_d (t) = A_d e^{-jwt}$ (from eq 2.27)

$a_d (t) = 0.02557e^{-jwt}$

The useful power extracted for work from the driving circuit

$P_{work} = 2\ \Gamma_{work}\ |A_d|^2$ (from eq 2.30)

$P_{work} = 2 \times 45{,}859.97 \times 0.02557^2$

$P_{work} = 60$ W

Radiated or scattered power is

$P_{rad} = 2\ \Gamma_s^{rad}\ |A_s|^2 + 2\ \Gamma_d^{rad}\ |A_d|^2$

$P_{rad} = (2 \times 958.095 \times 0.02927^2) + (2 \times 958.095 \times 0.025576^2)$

$P_{rad} = 2.895$W

Power absorbed at the source is

$P_s = 2\ \Gamma_s^{abs}\ |A_s|^2$

$P_s = 2 \times 5{,}714.26 \times 0.02927^2$

$P_s = 9.791$W

power absorbed at the device is

$P_d = 2\ \Gamma_d^{abs}\ |A_d|^2$

$P_d = 2 \times 5{,}714.26 \times 0.025576^2$

$P_d = 7.476$W

Efficiency

$n = P_{work} / P_{total}$

$P_{total} = P_{work} + P_{rad} + P_s + P_d$

$P_{total} = 60 + 2.895 + 9.791 + 7.476$

$P_{total} = 80.162$W

$n = 60 / 80.162 \times 100$ $n = 74.848\%$

CHAPTER FOUR

4.1 DISCUSSION OF RESULTS

After carrying out all the calculations, various graphs were plotted using MATLAB (see code in appendix B) to show how various parameters of the transfer scheme changed with the distance between the source and the device loops.

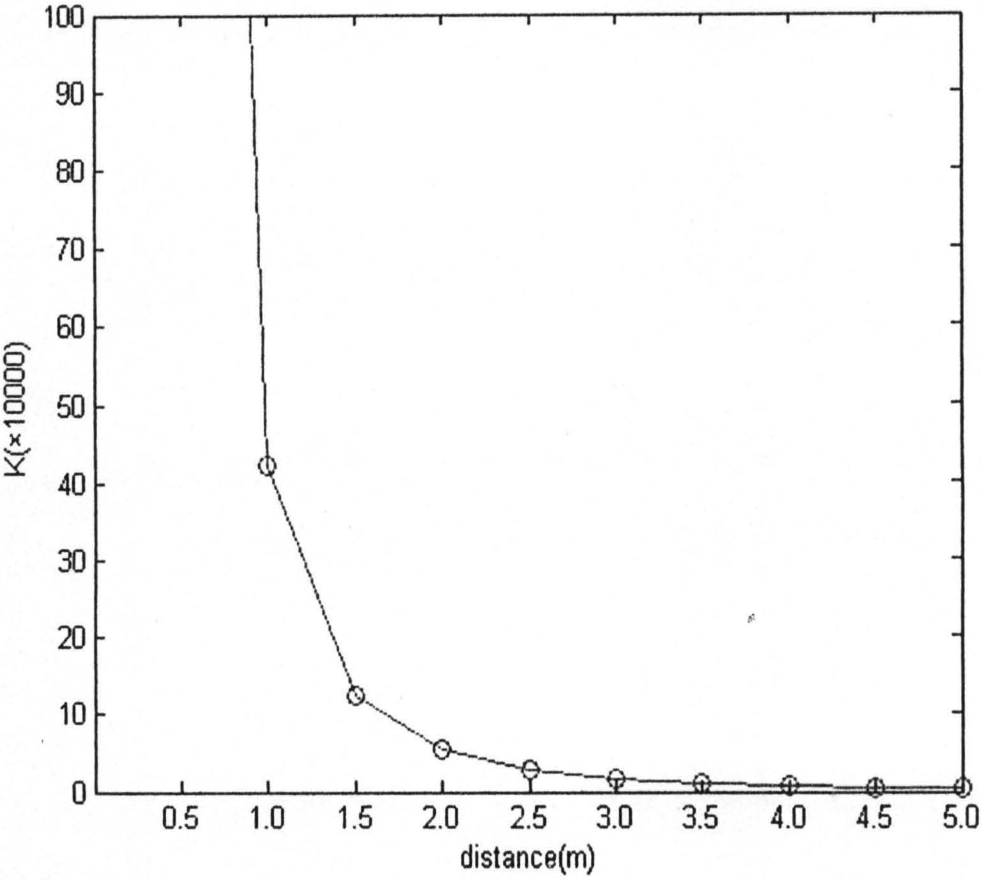

Fig 4.1 plot of coupling factor against distance between loop centers

From the plot above, as the two coils are farther separated, the coupling between them decreases hence interactions between their fields also reduce. The plot also shows that the coupling is stronger at midrange distance i.e when D/r is between 2 to 3, at these distances, more power can be delivered from source to device. When D/r exceeds this values, coupling becomes weak and little or no power will be delivered from source to device.

Another graph was plotted to study the effects of distance on the coupling to loss ratios (for code used see appendix C)

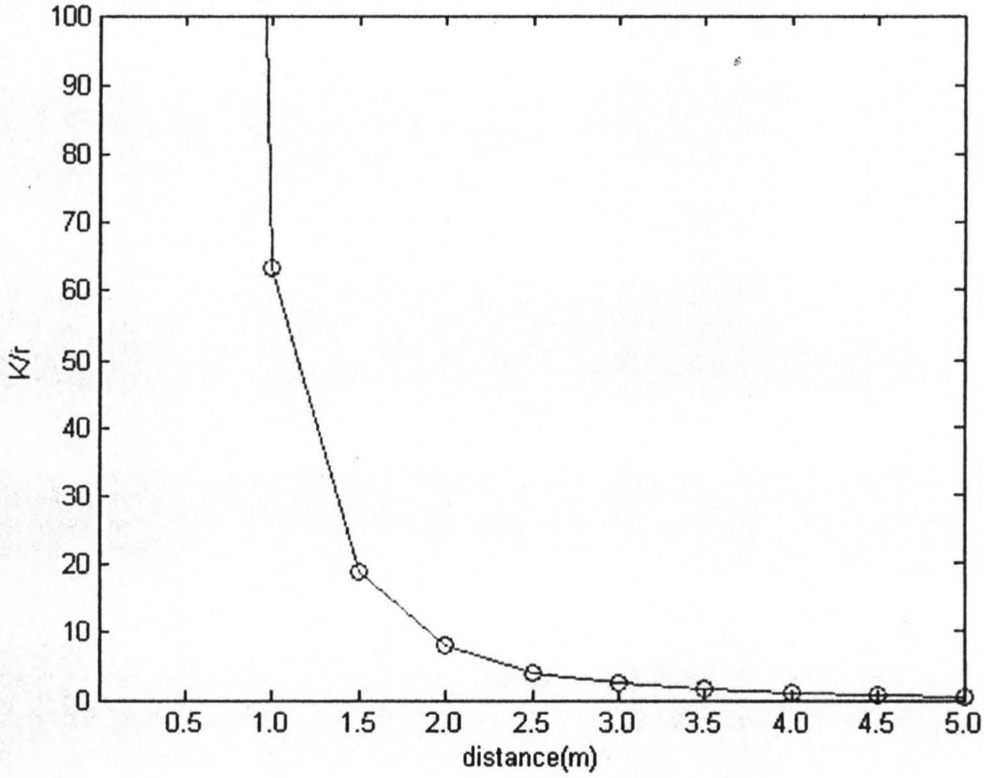

Fig 4.2 plot of coupling to loss ratios against distance between loops

As the two coils are being taken farther apart, the coupling to loss ratio approaches unity i.e k / Γ tends to 1. From the theory, it has being established that efficiency increases when $k / \Gamma >> 1$, thus it can be concluded that as the loops are taken farther apart, efficiency will decrease due to the decreasing coupling to loss ratio.

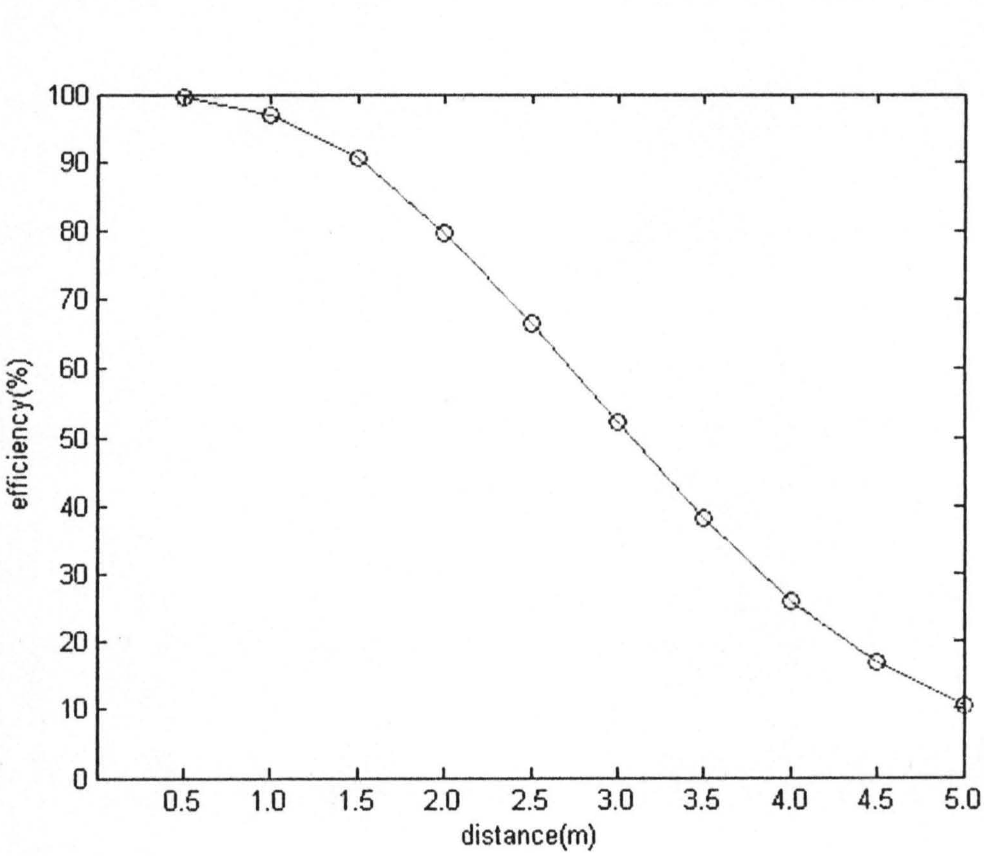

Fig 4.3 plot of efficiency against distance between loops

The efficiency of the scheme decreases as the coils are taken farther apart (see appendix D).

Safety of the system

The calculated scattered or radiated power $P_{rad} = 2.895W$ when the distance between the coil and the device was 2m which is not too higher than power emitted by cell phones (about 2W). At a distance hallway between the source and the device coils, field values were calculated to be, $E_{RMS} = 1.4KV$, $H_{RMS} = 8$ A/m and $S_{RMS} = 0.2$ A/m^2. These values fall below the IEEE safety standards for general safety exposure which shows that the transfer scheme is indeed safe.

CHAPTER FIVE

5.1 CONCLUSION

Useful power can be sent wirelessly over midrange distances with a high efficiency provided the sending and the receiving devices are at resonance.

5.2 LIMITATIONS

Since this project is mainly hypothetical, the major limitation is that it is not being implemented. This is due to the fact that the materials required for the implementation were too expensive.

5.3 SUGGESTIONS FOR FURTHER WORK

The following suggestions are made for further work in respect of this project.

1. Before any further advancement on this project, the effect of external objects should extensively studied to see the extent to which they may affect the transfer efficiency.
2. Although the two loops are currently of identical dimensions, it is possible to make the device loop small enough to fit into portable devices without decreasing the efficiency. One could, for instance, maintain the product of the characteristic sizes of the source and device coils constant.
3. The efficiency of the scheme and the power transfer distances could be appreciably improved by silver-plating the coils, which should increase their Q, or by working with more elaborate geometries for the resonant objects.

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APPENDIX A

Java code used to get table 3.1

Main.java

```java


package table;

/**@program Wireless Power Range Calculator
 * @version 1.0
 * @author shuaibu
 */

    public class Main {

            /**
             * @param args the command line arguments
             */
    public static void main(String[] args) {
        // TODO code application logic here
        double D, r1, r2, Uo, w, Ls, Ld, T;
        double M, K, Q, KT, K2T2, W2k, N;
         double PI = 3.14285714;


         r1 = r2 = 0.3;                    // r1 = r2 = 0.3m

         Uo = 4 * PI * Math.pow(10.0, -7.0);      // μ0  = 4 π  × 10^(-7) H/m

         w = 55.84 * Math.pow(10.0, 6.0);       // ω = 55.84 × 10^(-6) Hz

         Ls = Ld = 1.05 * Math.pow(10.0, -6.0); // Ls =Ld = 1.05 × 10^(-6) F

         T = 6672.35;                      // Γ =  6,672.35

         D = 0.0;                          //Initializes D to 0.0 before use

         //Prints the heading for the table; each \t means 5 spaces, \n = newline
 System.out.print("D \t\t M \t\t\t k \t\t\t Q \t\t\t K/T \t\t\t k2/T2 \t\t\t w/2k \t\t n(%) \n");
```

```
        //creates a loop to go round 30 times to change D from 0.5 to 5.0
        for (int i = 0; i < 10; i++)
           {
              System.out.print("\n"); //print a new line

              D += 0.5;//the value of D is incremented by 0.5
              System.out.print(D); //print D
              System.out.print("\t");//and leaves 5 spaces

              M = (((PI / 2) * Uo) * Math.pow(r1 * r2, 2.0)) / Math.pow(D, 3.0);
              System.out.print(M); //print M
              System.out.print("\t");//and leaves 5 spaces

              K = (w * M ) / (2 * Ls);
              System.out.print(K); //print k
              System.out.print("\t");//and leaves 5 spaces

              Q = w / (2 * T);
              System.out.print(Q); //print Q
              System.out.print("\t");//and leaves 5 spaces

              KT = K / T;
              System.out.print(KT); //print (k/Γ)
              System.out.print("\t");//and leaves 5 spaces

              K2T2 = Math.pow(K, 2.0) * Math.pow(T, 2.0);
              System.out.print(K2T2); //print (κ²/Γ²)
              System.out.print("\t");//and leaves 5 spaces

              W2k = w / (2.0 * K);
              System.out.print(W2k); //print (ω / 2k)
              System.out.print("\t");//and leaves 5 spaces

              //N is first given a temporary value of the numerator
              N =  Math.pow(1 + ( (K*K)/ (T*T) ),0.5) * ( (K*K)/ (T*T) );
                N = N / (double)(((K*K)/ (T*T) + N)+ Math.pow((Math.pow(1.0 + (1.0 + (K*K)/ (T*T) ),0.5)),2.0) );
              // N = N * 100; //if you want it in percentage remove the first //
              System.out.print(N); //print N
              System.out.print("\t");//and leaves 5 spaces



     }

```

```
}
}
```

APPENDIX B

MATLAB code used to plot fig 4.1

```
>> x = [1:10]; y=[338.323,42.290,12.530,5.2863,2.707,1.566,0.980,0.661,0.460,0.340];
plot(x,y,'o',x,y), set(gca,'XTicklabel',['0.5'; '1.0';'1.5'; '2.0';'2.5';'3.0';'3.5';'4.0';'4.5';'5.0';]),
set(gca,'XTick',[1:10]), axis([0 10 0 100]), xlabel('distance(m)'),
ylabel('K(×10000)')
```

APPENDIX C

MATLAB code used to plot fig 4.2

```
>> x=[1:10]; y=[507.052,63.383,18.779,7.922,4.056,2.347,1.478,0.990,0.696,0.507];
plot(x,y,'o',x,y), set(gca,'XTicklabel',['0.5'; '1.0';'1.5'; '2.0';'2.5';'3.0';'3.5';'4.0';'4.5';'5.0';]),
set(gca,'XTick',[1:10]), axis([0 10 0 100]), xlabel('distance(m)'),
ylabel('K/r')
```

APPENDIX D

MATLAB code used to plot fig 4.3

```
>> x = [1:10]; y=[99.60,96.95,90.41,79.82,66.46,52.09,38.16,26.01,16.70,10.38];
plot(x,y,'o',x,y), set(gca,'XTicklabel',['0.5';'1.0';'1.5'; '2.0';'2.5';'3.0';'3.5';'4.0';'4.5';'5.0';]),
set(gca,'XTick',[1:10]), axis([0 10 0 100]), xlabel('distance(m)'),
ylabel(' efficiency(%)')
```