MIT Sea Grant - AUV Laboratory

Highly Resonant Induction Power Transfer for Underwater Battery Recharging

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I. **Abstract –** Highly resonant induction power transfer systems are investigated in this paper. Underwater feasibility of such a system is compared to in-air test results. Through experimentation it is shown that a 4-coil highly resonant inductive power transfer system is preferable over a 2-coil inductive power transfer system because of the significantly higher quality factor provided by the 4-coil system.

II. Introduction

Nicola Tesla first advocated wireless power transfer over large distances over a hundred years ago. While the idea never fully transformed into anything other than in low power applications, recent developments over the last ten years have brought it back into the spotlight.

Typically induction power transfer with an air core is extremely inefficient once the transmitter and receiver coils are separated a few centimeters or misaligned. A system that has the ability to transfer power efficiently over a few meters, while simultaneously allowing for coil misalignment, would be much more beneficial to everyday use.

Experiments with a highly resonant 4-coil induction power transfer system have shown that high efficiency can be achieved over a range of the radius of the coil. A 4-coil inductive power coupling system takes advantage of resonance to achieve a high quality-factor (Q) within the system. A high quality factor is shown to be a key component in transferring power efficiently over distances more than a few centimeters in both the reference material and experimental data.

III. **Overview of Inductive Power Transfer Systems**

Three separate inductive power transfer systems were experimented with to find out what properties would contribute to high efficiency in power transfer. The Quality factor (Q) has been shown to help overcome the difficulties of transferring power efficiently with an air cored inductive power system.

While the coil size and shape where shown to be important for power transfer, the transfer efficiency was strongly influenced by the resonance factor (Q) of the system. Quality factor is a property of resonant RLC circuits and is quantified by the ratio of the energy stored versus the energy lost per cycle. The use of resonance greatly increases the efficiency of power transfer between the transmitter and receiver because of this Q-factor. When an RLC circuit is operating at its resonant frequency the impedance of the inductor and the capacitor cancel out, thus minimizing losses within the circuit, and maximizes the power transferred to the purely resistive load.

Typically the coupling between transmitter and receiver coils defines the rate of energy transfer. Recent work has indicated that high Q systems make up for a low coupling between the transmitter coil and receiver coil [Cannon et al, 2009], and allow for a high efficiency system. High Q systems are created by making the series resistance very small. Experiments with these high Q systems have shown efficient power transfer of greater than 85% at distances of around the radius of the coil when the transmitter and receiver coil are of equal size and number of turns.

Experimentation with three separate systems (figure 2.1a-c) has shown the importance of a 4-coil system in determining a high Q-factor. Figure 2.1a shows the inductive power coupling circuit based on self-resonance. The self-resonant system is highly inefficient and power transfer drops quickly if the transmitter and receiver coils are not very close and aligned. This is because this systems efficiency is based on the coupling coefficient (k) of the transmitter and receiver coils. Size, shape, distance, and orientation of coils determine the coupling coefficient. Figure 2.1b shows the inductive power coupling circuit based on parallel resonance. When this circuit is operating at its resonant frequency the impedance of the inductor and the capacitor cancel out and maximizes the power transferred to the purely resistive load. The parallel resonant configuration produces a low Q system and thus does not efficiently transfer power. Figure 2.1c shows a four coil resonant inductive power coupling circuit using series resonance. The low series resistance of the coils produces a high Q system.

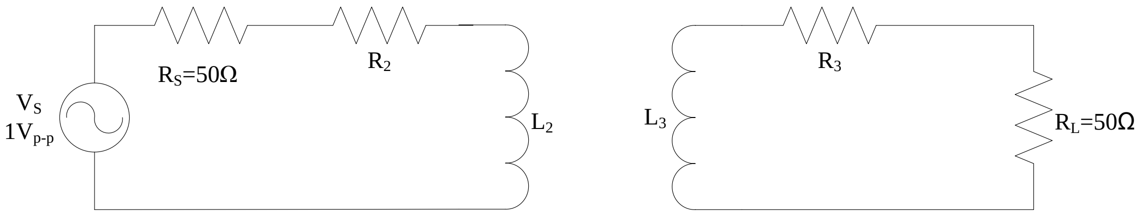

Figure 2.1a Self-Resonant Inductive Power Coupling

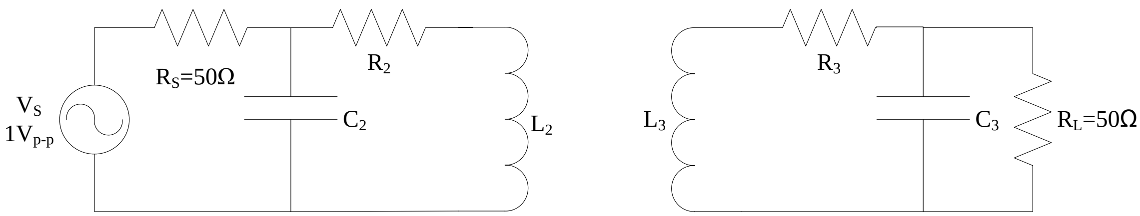

Figure 2.1b Two-Coil Resonant Inductive Power Coupling

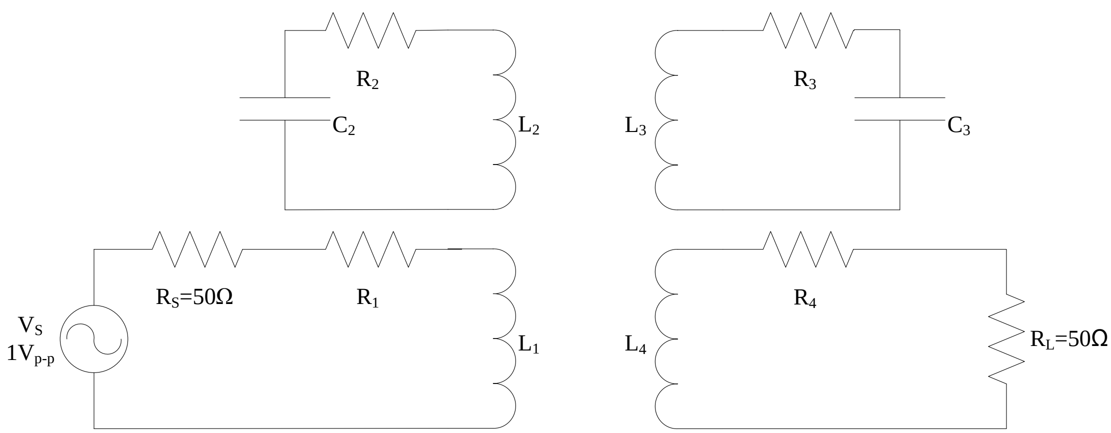

Figure 2.1c Four-Coil Highly Resonant Inductive Power Coupling

Resonance is a property of a Resistor, Inductor, and Capacitor (RLC) system. Adding a capacitor in series or parallel to the receiver coil, which is an inductor, will create a potential resonant circuit. Resonance will occur at a specific input signal frequency based on the values of the RLC system (equation 1/2).

$$\omega_o = \frac{1}{\sqrt{LC}} \qquad (1)$$

$$f_o = \frac{1}{2\pi \cdot \sqrt{LC}} \tag{2}$$

Resonantly coupled systems will form a single system that will resonant in two modes (frequency splitting), one lower frequency (odd mode) and one higher frequency (even mode) around the fundamental resonant frequency. Figure 2.2 shows this frequency splitting where the calculated resonant frequency is 660 kHz.

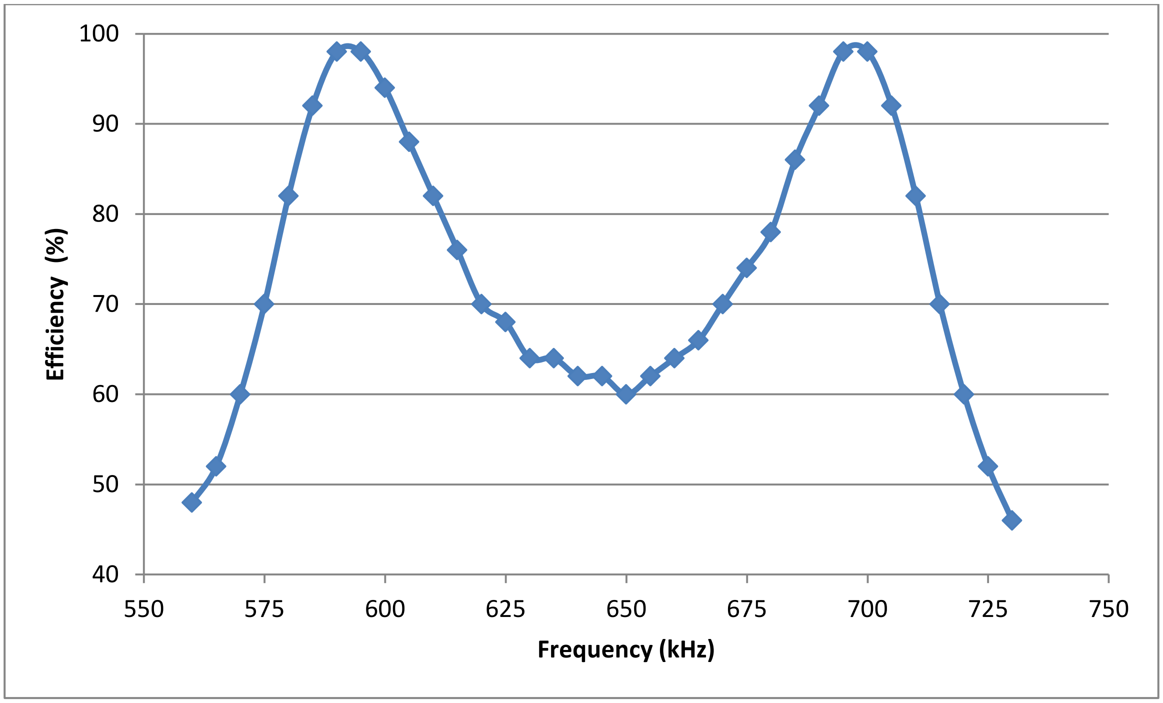

Figure 2.2 Frequency Splitting About the Resonant Frequency

The coupling of the coils can be calculated by (equation 3), [Kim et al, 2010] with the even and odd mode frequencies at a fixed separation and coil alignment.

$$k = \frac{M}{\sqrt{L_{Tx}L_{Rx}}} = \frac{M}{L} = \frac{f_{even}^2 - f_{odd}^2}{f_{even}^2 + f_{odd}^2} \tag{3}$$

The frequency at which these two resonant modes occur from the fundamental resonant frequency is dependent on the coupling coefficient (k) of the transmitter and receiver coils (equation 4).

$$f_{even} = \frac{f_o}{\sqrt{1-k}}, \quad f_{odd} = \frac{f_o}{\sqrt{1+k}} \tag{4}$$

This frequency splitting of the resonant frequency will converge onto the fundamental resonant frequency as transmitter and receiver coil distance increases, which will make the coupling between the coils smaller. The coupling between the coils will increase as the transmitter and receiver coils get closer together. Coupling is additionally determined by the angle between the coils and the shape of the coils.

Parallel resonant RLC circuits (figure 2.1b) have a Quality factor (Q_P) associated with the circuit that is defined by the ratio of the resistance to the reactance of the inductance at resonance. For the 2-coil system the Q-factor for the transmitter and receiver of the system is shown in equation 5.

$$Q_P = \frac{R_S+R_2}{\sqrt{\frac{L_2}{C_2}}} = \frac{R_L+R_3}{\sqrt{\frac{L_3}{C_3}}} \tag{5}$$

The 2-coil system is highly dependent on the value of the source and the load impedance. Because the 2-coil system is highly dependent on the source and load impedances the achievable system Q-factor cannot reach the higher required values for efficient power transfer. For this reason I did not include any tests from the 2-coil inductive power transfer system tests.

Series resonant RLC circuits (figure 2.1c) have a Quality factor (Q_S) associated with the circuit that is defined as the ratio of the reactance of the inductance at the resonant frequency to the resistance. For the 4-coil system the Q-factor for the transmitter and the receiver of the system is shown in equation 6.

$$Q_S = \frac{\sqrt{\frac{L_2}{C_2}}}{R_2} = \frac{\sqrt{\frac{L_3}{C_3}}}{R_3} \tag{6}$$

The 4-coil system removes the high source and load impedances from the system by inductively coupling the transmitting coil to the power source via a single turn drive loop, and inductively coupling the receiving coil to the load via a single turn drive loop. The systems Q-factor is now only dependent on the series resistances of the transmitter and receiver coils. This system easily achieves the high Q-factor values required to overcome the low coupling of the system and to transfer power efficiently over a significant distance.

Index: Experimental Set-Up and Results

IV. Experimental Set-Up and Results

1) Experimental Set-Up

There are two voltage sources (V_S) used for the following experiments, 1: BK Precision 4040A Function Generator, 2: ICOM IC-718 High Frequency Transceiver, which can operate at a higher power than the function generator but with limited operating frequencies. The HF transceiver is used in conjunction with the MFJ-993B Automatic Antenna Tuner. The automatic antenna tuner will introduce a series inductance and parallel capacitance into the transmitter circuit (figure 3.1), to match the impedances of the transmitter and receiver circuits.

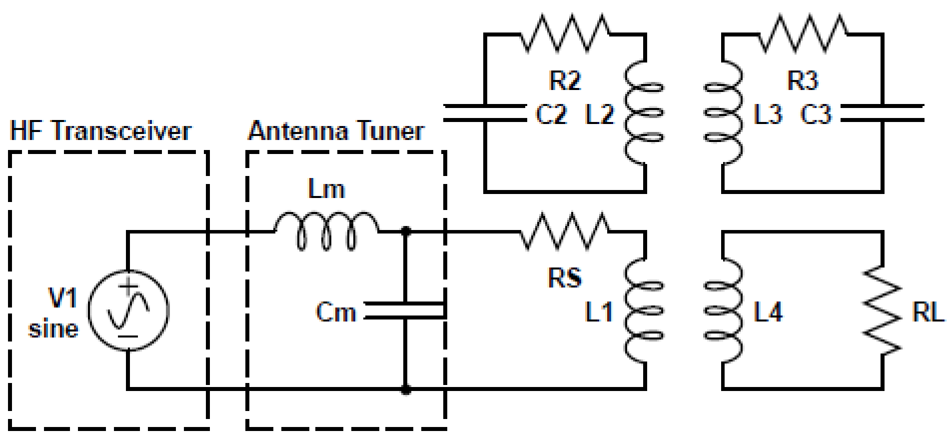

Figure 3.1 4-Coil Wireless Power Transfer Circuit

Highly resonant inductive power transfer systems will be examined in this paper. Throughout the experiments the open source voltage will be fixed and the frequency will be varied in order to find the resonant point at which the system operates. The source resistance (R_S) of both the function generator and the HF transceiver is 50Ω. The transmitter (L_2) and receiver coils (L_3) are the multi turn excitation coils used for transmitting and receiving power in the system. A Single turn coil that is connected to the voltage source is wrapped directly around the transmitter coil to inductively couple the power to the transmitter coil. The receiver coil is set up the same, but the difference is that the single turn power coil is connected the load. The power coils in the 4-coil system are used to inductively transfer power to their respective excitation coils and are represented by L_1 and L_4.

Each coil has a radius (a) of 15cm and is constructed of #10 AWG solid magnet wire unless otherwise noted. In order to have both the transmitting and receiving portion of the circuit operate at resonance it is important to set both C_2 and C_3 equal since L_2 and L_3 are equal. For experiments where L_2 and L_3 are not equal compensation based on calculations must be accomplished with varied C_2 and C_3 capacitors. Resistors 1-4 are the small resistances of the coils and are not added resistors to the system. R_L is selected based on maximum power transfer occurring when $R_S = R_L$ (Appendix C). Maximum power transfer for this system is shown by equation 7.

$$\frac{V_S^2}{4R_L} \tag{7}$$

For example the systems load (R_L) is a 50Ω resistor with $V_{OpenSource}$

set at 10V, so the maximum power transfer achievable by the system is 0.5W.

Varied tests were first performed in air to get an adequate understanding of the properties of a highly resonant inductive power transfer system, and the expected results of different experimental tests. From there underwater tests were performed first in freshwater and next in saltwater. Freshwater and saltwater experiments were conducted and compared to similar in air experiments.

a) Methods

i. Highly Resonant Inductive Power Systems

Four coil highly resonant inductive power transfer systems were chosen over traditional two coil inductive power transfer systems. Traditional two coil air core inductive power transfer systems have been shown to have low efficiency when in operation with an air core (Appendix A). Furthermore two coil systems power transfer efficiency drops even lower once the coils are no longer axially aligned and separated more than a few millimeters. For this reason all tests performed in this paper are of the four-coil highly resonant inductive power transfer type, which has been shown experimentally to have significantly higher efficiency of power transfer with less than ideal coil separation and alignment.

Figure 2.1c shows a highly resonant inductive power transfer circuit using series resonance. The voltage source (V_S) in this circuit is now connected to a single loop source coil (L_1) that is directly coupled to the transmitter coil (L_2). The transmitter coil is essentially floating so that it is not electrically connected to anything. The single loop source coil is wrapped around the transmitter coil to maximize the coupling coefficient between them. This will minimize losses and allow power to be transferred from the source coil to the transmitter coil. The receiver side is set up the same except that there is a single loop load coil (L_4) connected to R_L (figure 3.2).

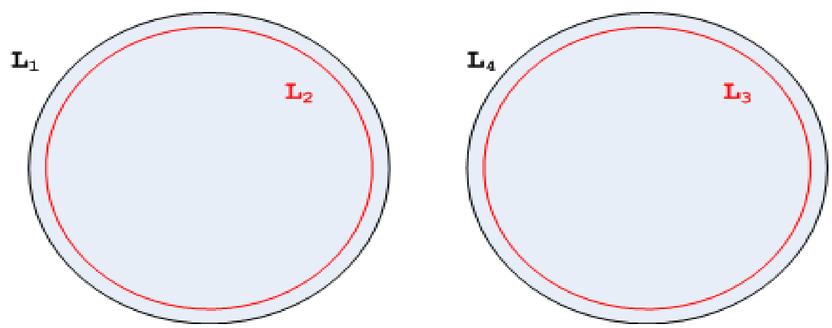

Figure 3.2 Top view of 4-Coil System

The single loop coils are used to separate the high impedances of the source and the load and will result in a higher Q-factor than is achievable by the 2-coil system. This is because the resistance determining the Q-factor is made up from the multi-turn copper coils that make up the transmitter and receiver. Since the resistance is very small it is possible to get a series Quality factor in the thousands. This has a significant impact on how well the power can be transferred from the transmitter coil to the receiver coils.

ii. Coil Shift Effect

Coil shift tests were performed by first axially aligning the transmitter and receiver coils over one another and finding the resonant frequency in which maximum power is transferred. Next leaving the transmitter coil in a fixed location the receiver coil is now shifted horizontally along the x-axis (figure 3.3a/b), by a percentage of the coils radius (a), and the frequency is then tuned to find the systems resonance. The frequency must be tuned each time either coils position is changed. This is due to the frequency splitting effect due to the change in the coupling coefficient as the coil position is changed. Figure 3.3 shows various distances between the fixed transmitter coil (blue) and the shifting receiver coil (yellow) from the center of the transmitter to the center of the receiver.

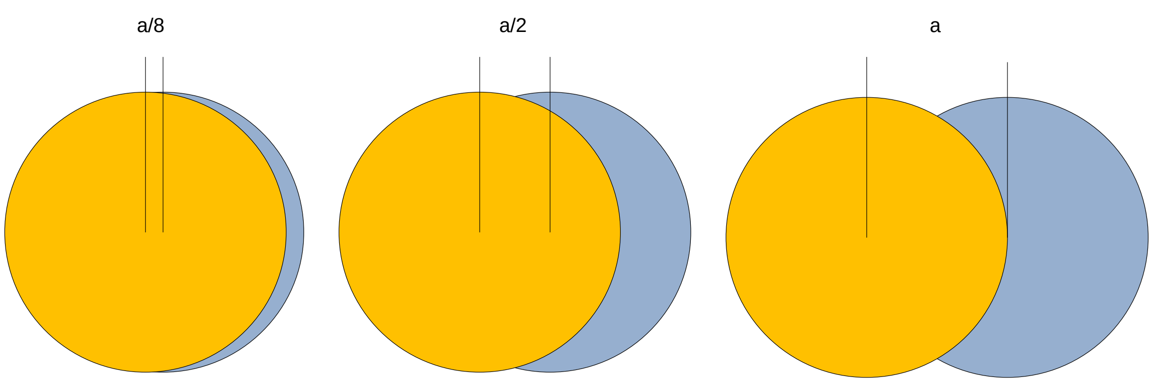

Figure 3.3a Top View of Coil Shift Effect in Receiver Radius (a)

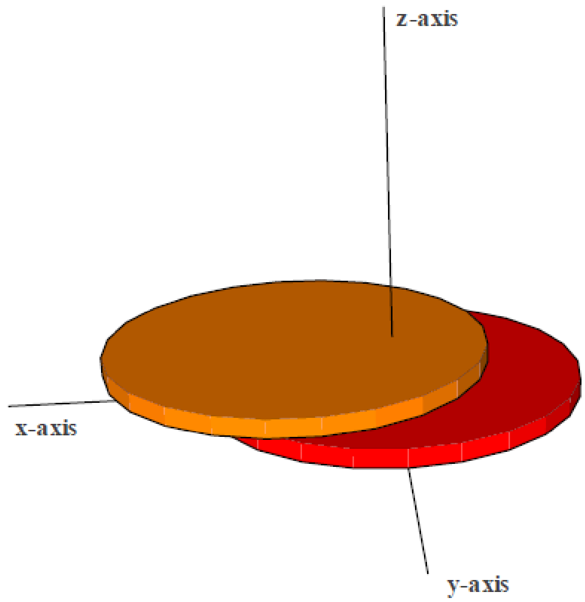

*Figure 3.3b Coil Shift Effect (0.5*radius shift)*

iii. Coil Separation Effect

Coil separation tests were performed by first axially aligning the transmitter and receiver coils over one another and finding the resonant frequency in which maximum power is transferred. Next leaving the transmitter coil in a fixed location the receiver coil is separated by a specific distance in centimeters along the z-axis (figure 3.4). The two coils remain axially aligned over one another. Due to the change in coupling that occurs between the two coils when the separation distance is changed, the frequency must be re-tuned to find the new resonant peak at which maximum power transfer occurs.

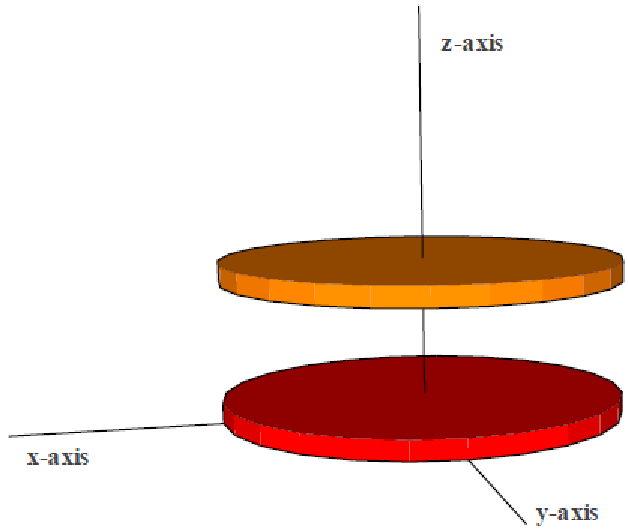

*Figure 3.4 Coil Separation Effect (1*radius separation)*

iv. Coil Shift + Separation Effect

Coil shift plus separation tests were performed by first axially aligning the transmitter and receiver coils over one another and finding the resonant frequency peak in which maximum power is transferred. Leaving the transmitter coil in a fixed location the receiver coil is first shifted by a percentage of the coils radius along the x-axis then separated from the transmitter along the z-axis at centimeter intervals up to a radius of the coil away (figure 3.5). Due to the change in coupling that occurs between the two coils when the receiver is shifted and/or the separation distance is changed, the frequency must be re-tuned to find the new resonant peak at which maximum power transfer occurs.

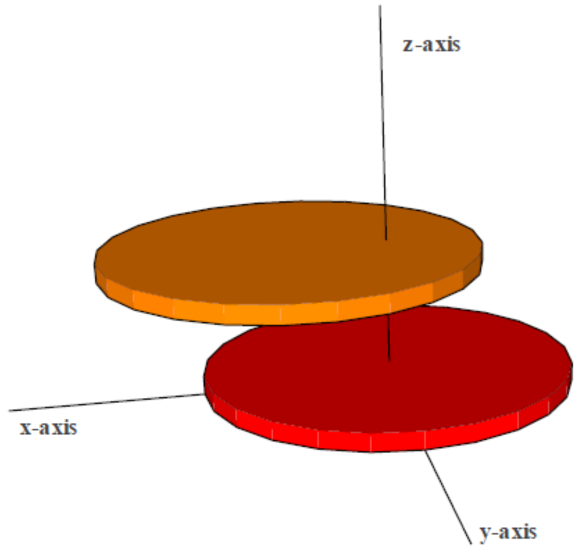

*Figure 3.4 Shift and Separation Effect (1*radius separation + 0.5*radius shift)*

v. Multiple Transmitter Coil Effect

Multiple transmitter coils were explored to see if the range of power transfer could be extended. Each single transmitter coils will have the same radius as the receiver coils. First two or more transmitter coils were connected electrically in parallel. These coils were fixed and lined up next to each other on the x-axis or placed in a group of four along the x/y-axis (figure 3.5).

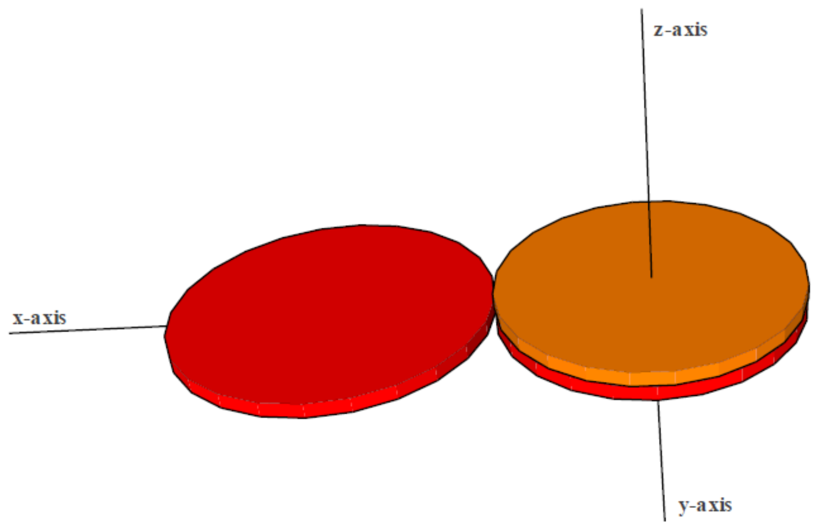

Figure 3.5 Multiple Transmitter Coil Effect Setup

Multiple coil tests were performed by first lining up the receiver coil above one of the transmitter coils and shifting the receiver coil about the x-axis by a percentage of the radius. Once the receiver coil was past the range of magnetic induction the test would be accomplished but first the receiver coil would be shifted by a percentage of the radius in the y-axis (figure 3.6).

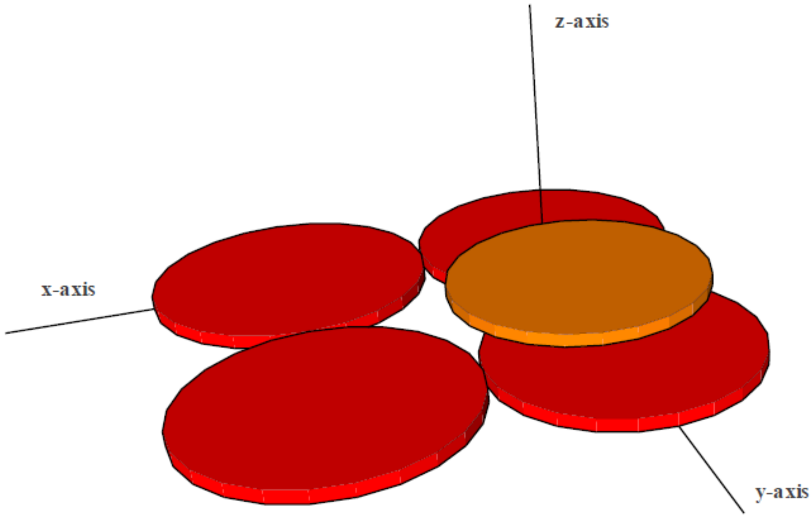

Figure 3.6 Four Transmitter Coil Setup (Rx Coil Starting y-axis position)

vi. Rounded Rectangle Coil Effect

Most of the tests involved two circular coils in which the turns ratio and inductance were the same. For a practical AUV recharging system a receiver coil would have to be stretched along the body of the AUV. Shift effect tests were performed keeping the original circular transmitter coil with the introduction of a rounded rectangular receiver coil (figure 3.7). The transmitter and receiver coils were kept at equal turn ratios and the radius of the coils were also kept to be equal. The two sets of coils were also tuned to the same resonant frequency.

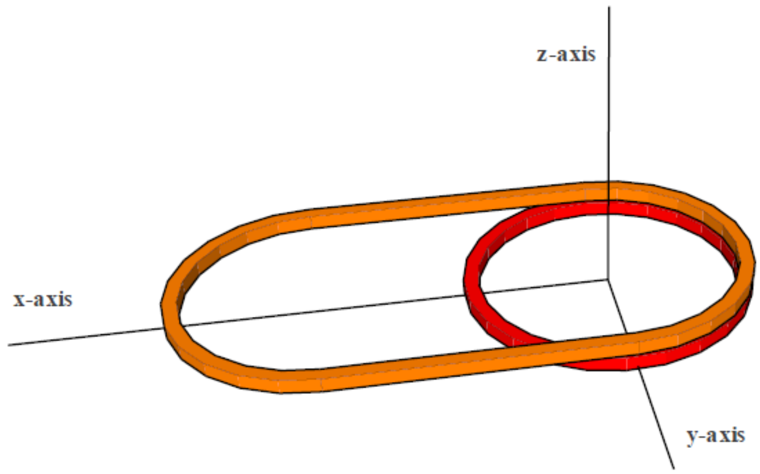

Figure 3.7 Rounded Rectangular Coil Setup

vii. Magnetic Material

Magnetic shielding tests were performed by fixing a magnetic barrier behind the receiving coils. The coils are always axially aligned with one another, but measurements are taken as the coils are separated further away from each other. A small search coil is used to measure the voltage induced in the coil at fixed distances behind and around the receiver coil. The search coil was first placed just behind and in the middle of the receiver coil. Search coil voltages are then recorded as the search coil is along the x-axis. Next the search coil is moved back a specific distance and the shift test of the search coil is repeated.

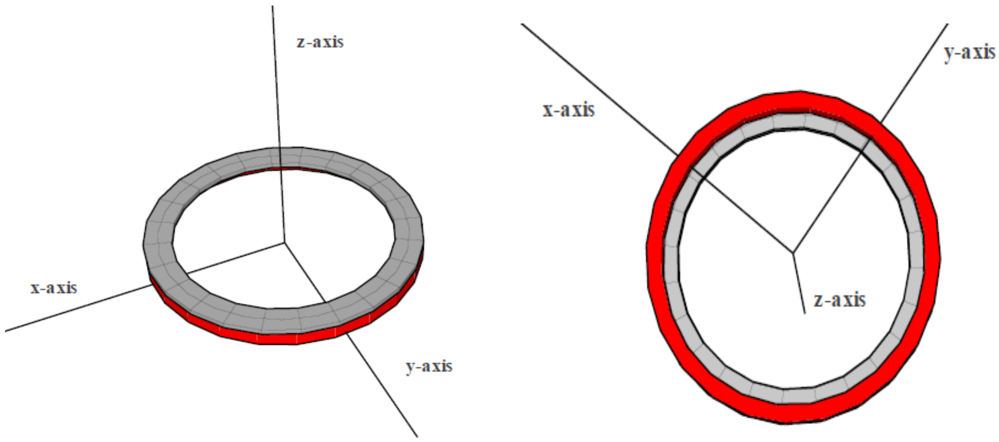

Figure 3.8 Top and Bottom View of Magnetic Material on Coil

viii. Water Effect

Freshwater/saltwater tests were performed with different coil configurations. Each successive configuration was developed to overcome a previous challenge with the effects of the water on the magnetic field. Similar tests to that in air were performed to compare the results to from the freshwater/saltwater experiments to the air experiments.

2) Results

A. Spacing

2.1 Coil Shift Effect

With the transmitting coil in a fixed location the receiver coil can be moved along the x-axis of the transmitter coil and transfer power at above 90% efficiency up until the radius of the coils before power transfer efficiency begins to decrease (figure 3.9).

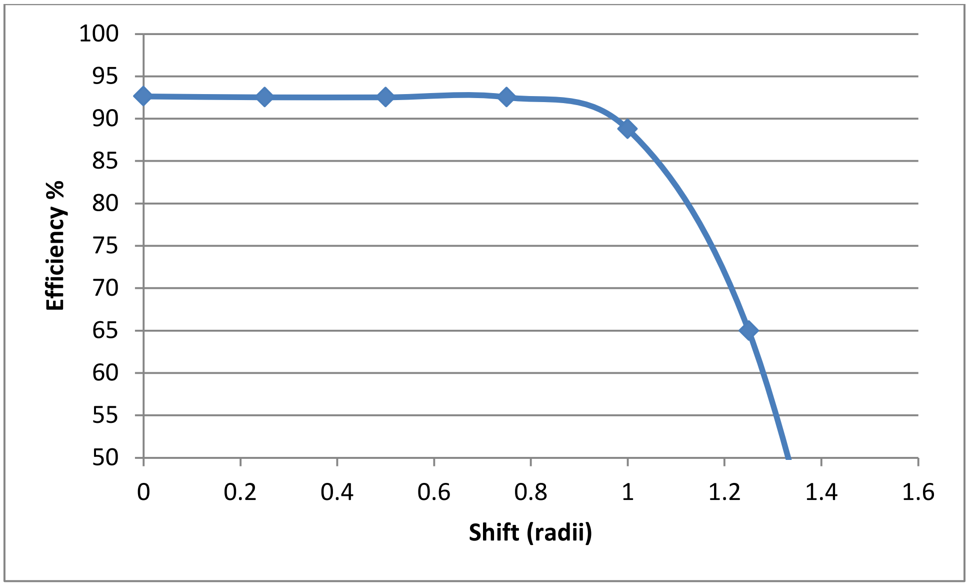

Figure 3.9 Efficiency Vs. Receiver Coil Shift

2.2 Coil Separation Effect

With the transmitting coil in a fixed location the receiving coil can now be separated by up to a full radius in distance (z-axis) from the transmitter coil before power transfer efficiency begins to significantly decrease (figure 3.10). From these two figures it is possible to see the significant impact of highly inductive power coupling systems.

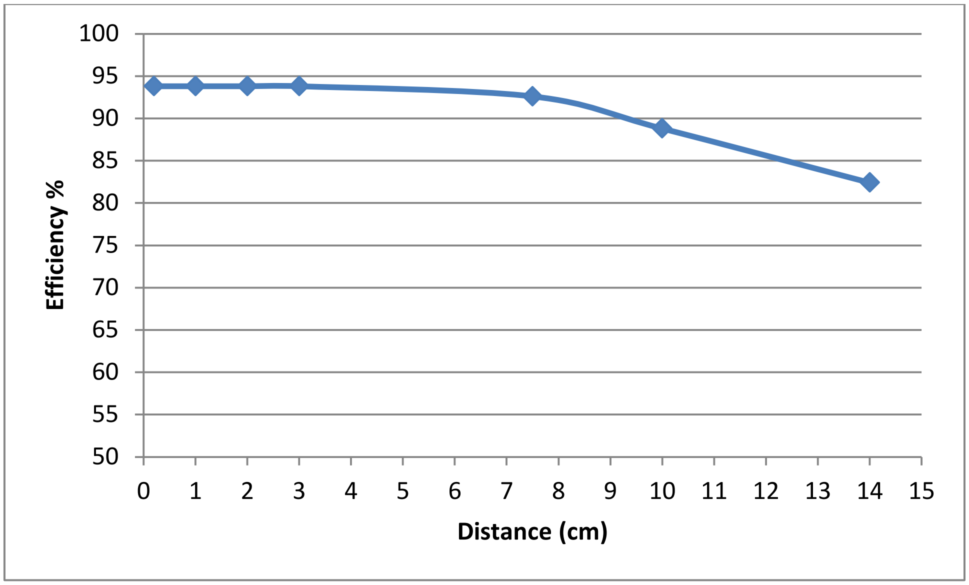

Figure 3.10 Efficiency Vs. Receiver Coil Separation

2.3 Coil Shift + Separation Effect

For this test the transmitting coil is in a fixed location and the receiver coil is first shifted about the x-axis by a percentage of the coil radius and then separated about the z-axis. The results show that it is possible to keep efficiencies above 80% while the receiver coil is shifted by almost a full radius and separated by up to a full radius (figure 3.11).

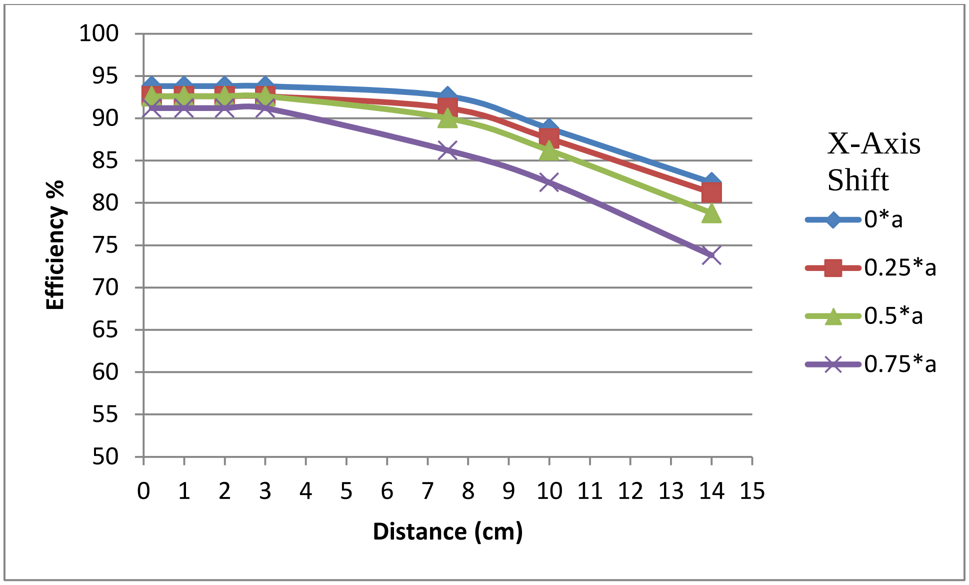

Figure 3.11 Efficiency Vs. Shift + Separation

B. Geometry

2.4 Rounded Rectangle Effect

For this test a single transmitter coil was fixed and the rounded rectangle receiver coil was shifted in the x-direction (Appendix D). The receiver coil was next shifted and fixed in the z-direction by a percentage of the radius, and the x-direction shift test was again accomplished (figure 3.12).

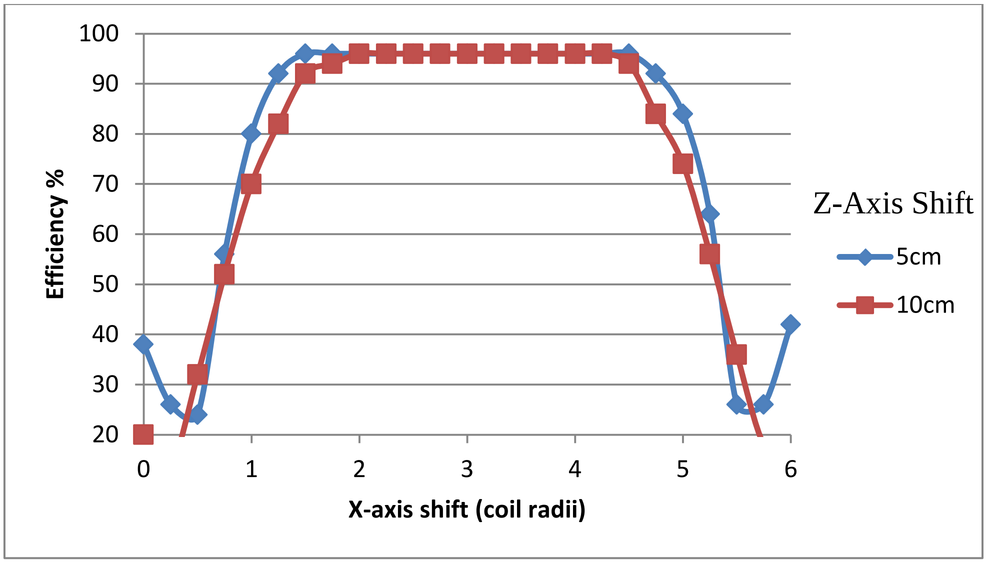

Figure 3.12 *Rounded Rectangle Coil Shift Test with Varied Fixed z-axis Receiver Coil Locations*

2.5 Multiple Transmitter Coil Effect

Multiple transmitter coils with a single shared power source were set up in a fixed position to show the effect of a possible multi-coil power transfer pad. Shift effect results of a single transmitter coil with a single receiver coil were compared to tests with multiple transmitter coils with a single receiver coil (Appendix D). The results show that the range can be extended when the multiple transmitter coils are connected in parallel verses being connected in series (figure 3.13). Connections to each transmitter coil must be in such a way as to produce magnetic fields that are in the same direction. If not the magnetic fields produced by each transmitter coil will cancel part of the others out.

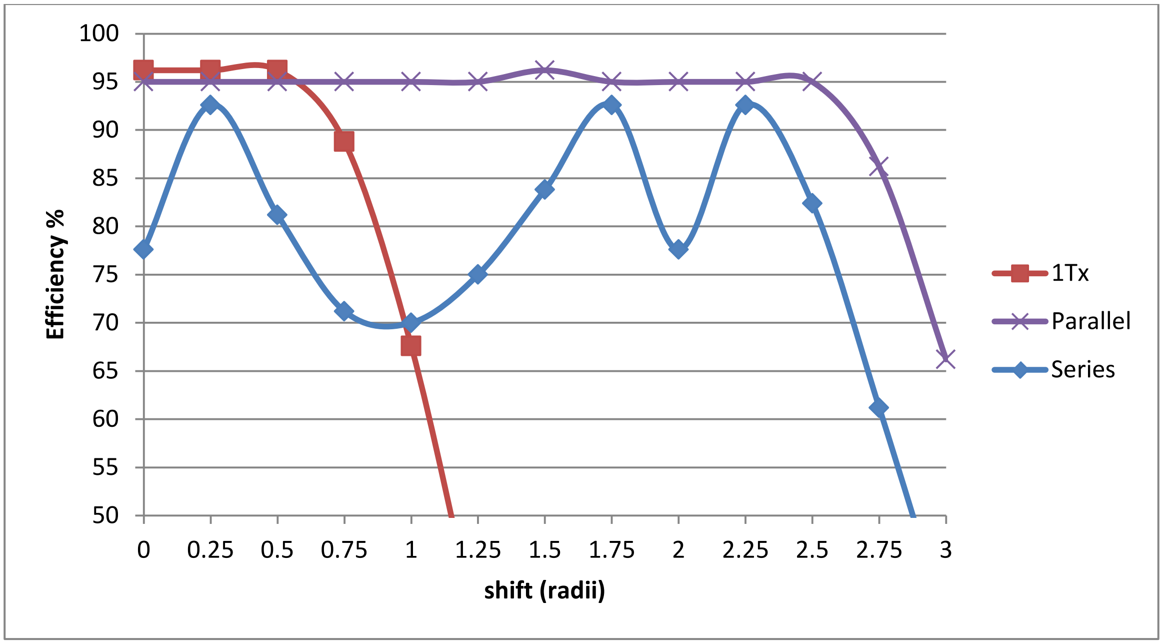

Figure 3.13 Two Transmitter Coils Connected in Series and Parallel Compared to Single Transmitting Coil

The next test is to show the range in which the coils can transfer power efficiently. A shift test is performed with the transmitter and receiver coils centered on each other and then the receiver coil is shifted into a new fixed location on the y-axis by a percentage of the radius (Appendix D). A new shift test is performed about the x-axis with the receiver coil in a new y-axis fixed location. Both the transmitter and receiver coils are equal in size. The results show that up until a half of a radius the coils are able to transfer power efficiently (figure 3.14). The dip in the middle of the test is due to the cancelation effect of the two magnetic fields produced by the two transmitting coils.

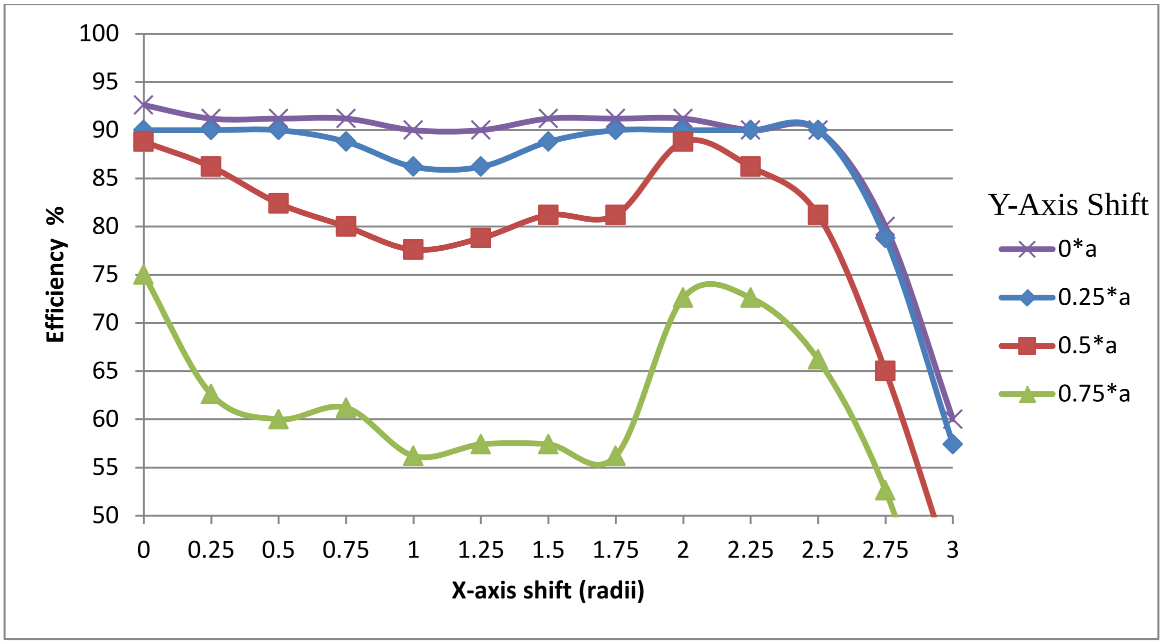

Figure 3.14 Two Transmitter Coil Shift Test with Varied Fixed y-axis Receiver Coil Locations

Two transmitter coil tests were performed with a rounded rectangular receiver coil (Appendix D). These tests show that an extended range is possible with a longer coil in as the receiver (figure 3.15). Again it is shown that there is a slight dip when the receiver coil in centered upon both transmitter coils from the cancelation of the magnetic fields of both transmitter coils.

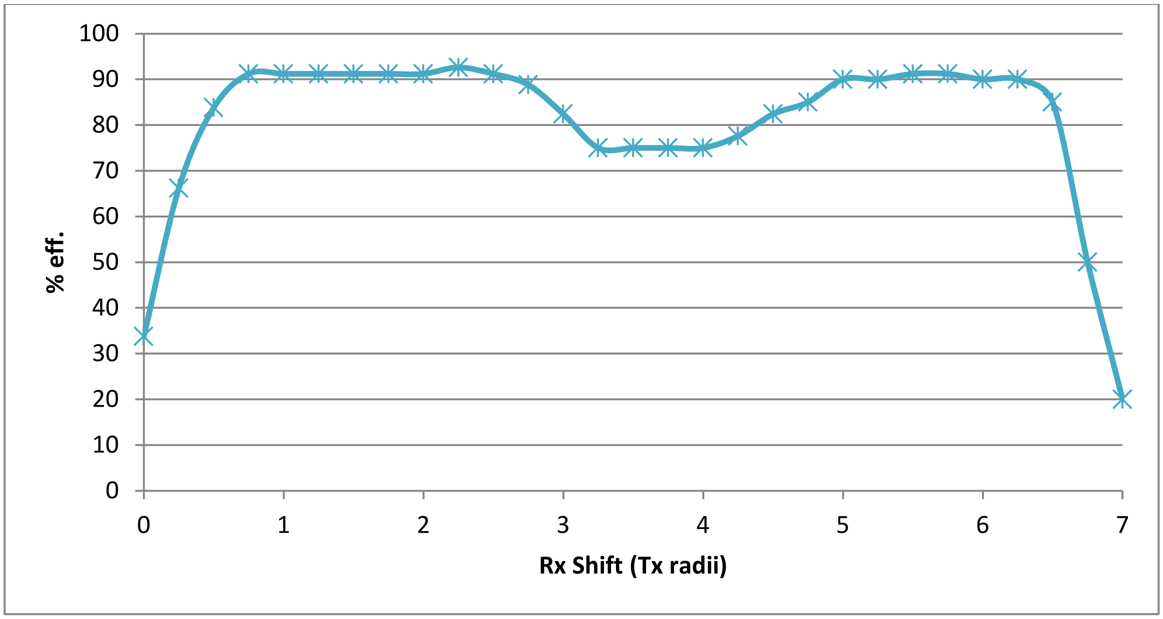

Figure 3.15 Two Transmitter Coil Shift Test with Rounded Rectangular Receiver Coil

The next multiple transmitter tests were performed to show the efficiency of power transfer between four transmitter coils (Appendix D) and a single receiver coil. Tests were accomplished using a single receiver coil that was the same size as one of the transmitter coils (figure 3.16), as well as a single rounded rectangular coil (figure 3.17). The receiver coil is first lined up in the middle of the four transmitter coils (0*a) and shifted in the x-direction. Next the receiver coil is shifted in the y-direction by a quarter of the radius and again shifted in the x-direction.

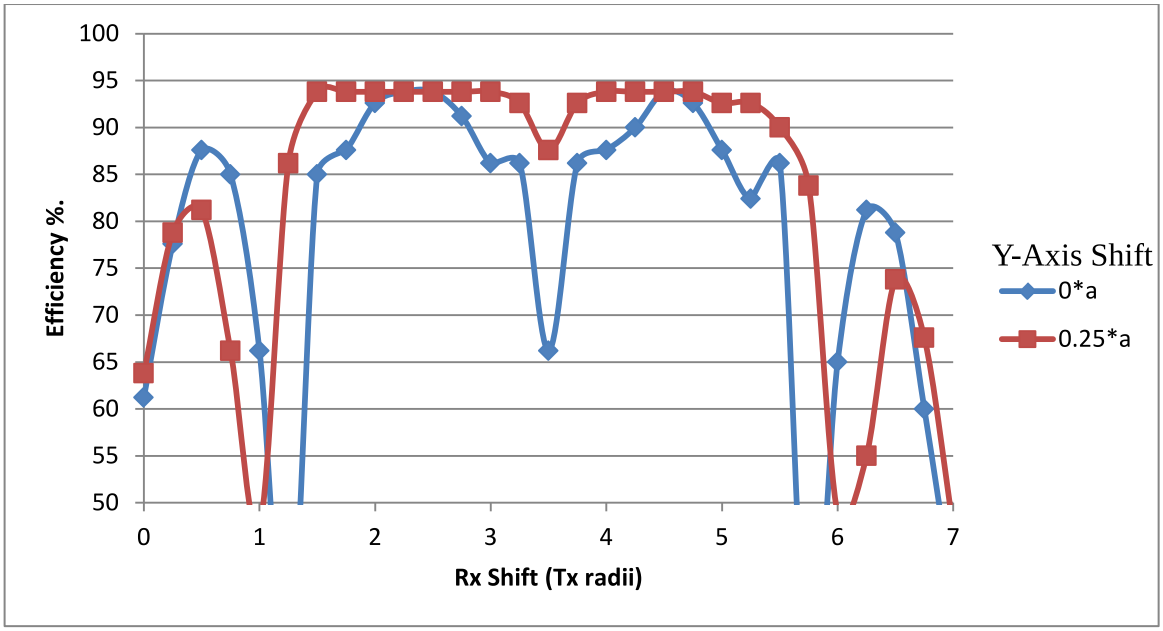

Figure 3.16 Four Transmitter Coil Shift Test with Varied Fixed y-axis Receiver Coil Locations

Results from the equal sized transmitter and receiver coil tests show that there is an increase in power transfer range in the x and y axis directions. Efficiency begins to improve as the transmitter and receiver coils begin to line up over one another. The dips in efficiency occur when the transmitter and receiver coils are not optimally aligned (receiver shifted >radius of coils). The tests also showed that the magnetic fields of each coil would infringe on one another if all four coils were powered at the same time. It was found that the best configuration was to short out the receiver coil that is not optimally aligned to the receiver coil.

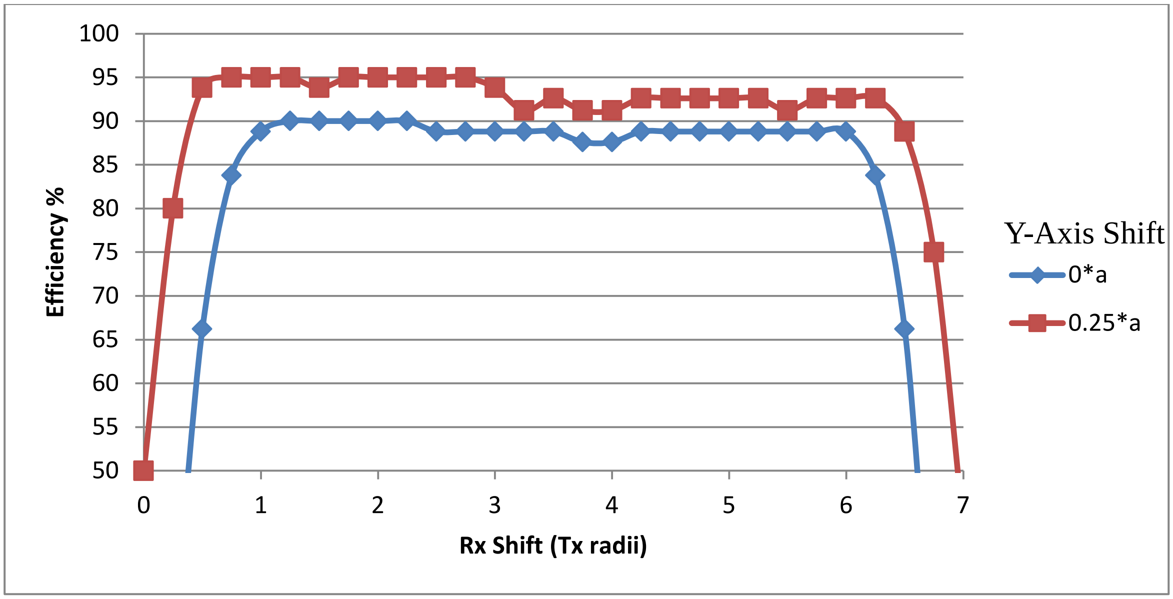

Figure 3.17 Four Transmitter Coil Shift Test with Rounded Rectangular Receiver Coil

The results from the rounded rectangular receiver coil show a better resulting interaction between multiple transmitter coils and a receiver coil. The rectangular receiver coil does not negatively interact with the extra transmitter coils as does the equal sized transmitter and receiver coils.

2.6 Coil Diameter Effect

Changes in coil diameter tests are performed to explore power transfer efficiency of a receiver coil 50% larger than the transmitter coil. The receiver coils radius is two times that of the transmitting coil (Appendix D). Shift effect tests are performed (figure 3.18) using a single transmitter coil with a receiver coil that is 50% larger (blue curve) and compared to results when both coils are equal (red curve).

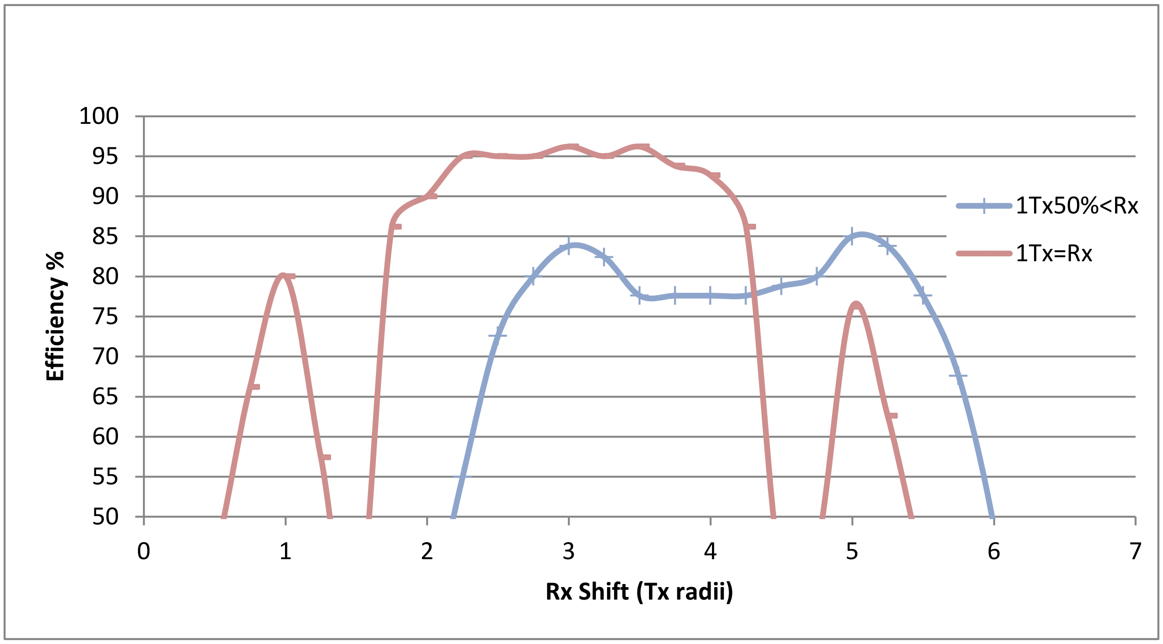

Figure 3.18 Receiver Coil 50% Larger than Transmitter Coil

The results show that the optimal configuration of the coils is such that the radius of the transmitter coil is equal to that of the receiver coil for maximum power transfer to occur. This is highlighted by previous test results that show a rounded rectangular receiver coil that is two times as long as the transmitting coil, but having a radius that is equal to the transmitter coil, transmitting power just as effectively as two coils that are the same shape and radius.

C. Magnetic Material

2.7 Ferrite Material

The magnetic fields that make is possible to transfer power could also have a negative effect on system performance if allowed to extend past the receiver coil. Effects of magnetic materials are explored by placing ferrite material behind the receiver coil. Magnetic flux lines produced by a current flowing in a coil will concentrate closer to the coils center to the coil perimeter. After the coils perimeter the flux lines tend to spread apart (figure 3.19)

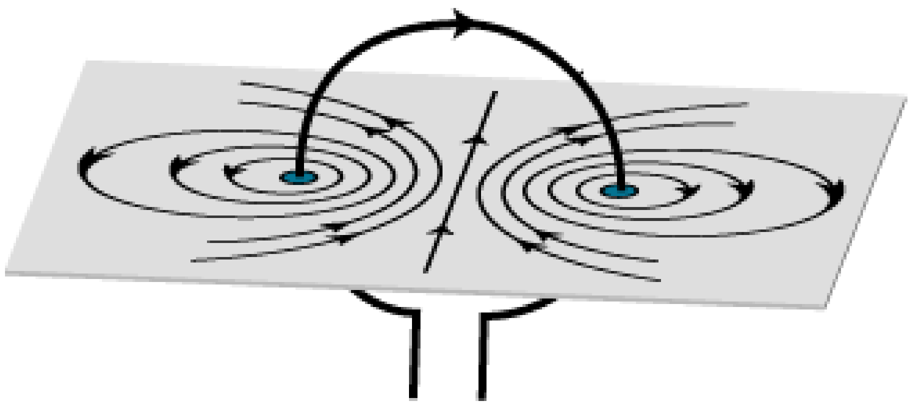

Figure 3.19 Magnetic Flux Lines around a Current Carrying Coil

The magnetic material behind the receiver coil will serve to both limit the amount of magnetic flux that extends beyond the coil, as well as shape the magnetic field such that the receiver coil absorbs larger amounts of magnetic flux. As shown in figure 3.20, the magnetic material that is placed directly behind the receiver reduces the amount of voltage induced on the search coil that is placed 5 cm and 10 cm behind the receiver coil. Once the search coil extends past the perimeter of the receiver coil the voltage induced significantly decreases.

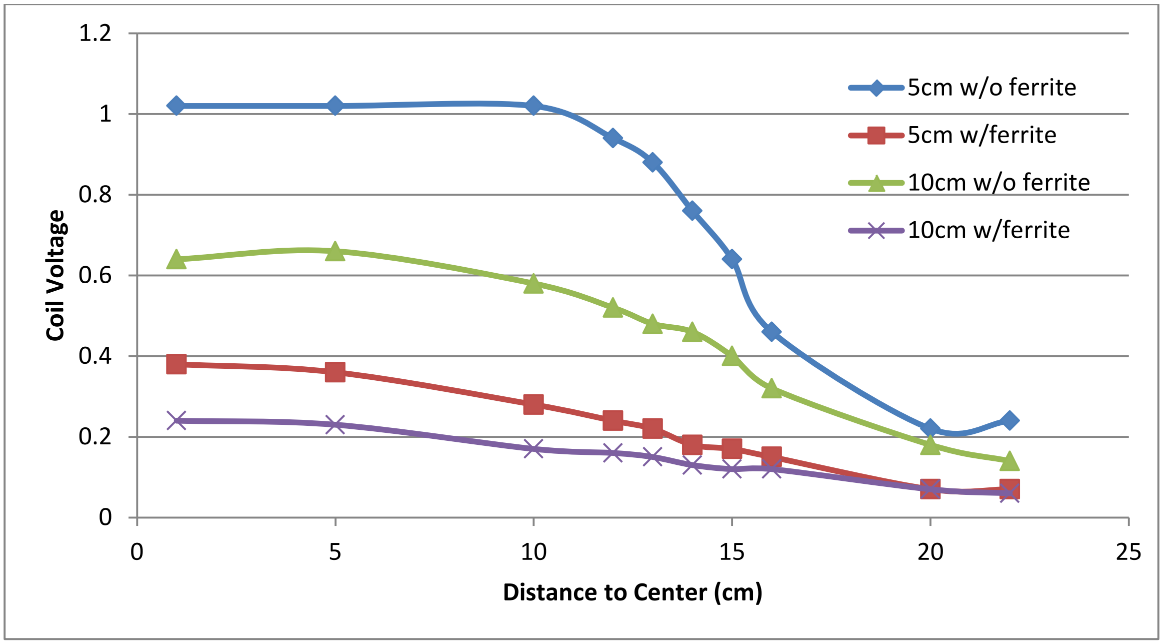

Figure 3.20 Search Coil Voltage, Center to >6cm Coil Perimeter

D. Water Effect

The effect of freshwater and saltwater efficiency of power transfer is explored. Until now all experiments have been done in air. Air has a different magnetic permeability (μ_o) than freshwater and saltwater, as well as a different conductivity (σ). Magnetic permeability is the measure of how strong a magnetic field will form within a material or medium. Conductivity is the measure of how well a material or medium will conduct electricity.

Both freshwater and saltwater produce problems that reduce the efficiency of the inductive power transfer system. The first problem arises from the difference in the dielectric constants (ϵ_o) of the materials, which is related to the magnetic permeability. The change that occurs to the dielectric constant when the coils are placed in the water, for freshwater (80) and saltwater (~85), is problematic compared to when the coils are placed in air (1). Another problem arises because saltwater is significantly more conductive than air or freshwater. This is because current is transported by the ions in salt water. The magnetic field produced by the transmitter creates eddy currents within the saltwater. The approach to solving the problems due to water effect is to use first principles.

2.8 Freshwater/Saltwater

The first underwater inductive charging tests were performed in freshwater. This was to limit the amount of factors that were introduced to the inductive charging system from that of air. Once the problems that were introduced by the freshwater into the inductive power transfer system were overcome the tests were repeated in saltwater, which add additional factors to overcome.

It was found that placing the coils directly in contact with the water, freshwater or saltwater, was detrimental to system performance. This brought efficiency down to less than 10%. The creation of fully waterproof boxes brought the efficiency back up to that was typical for the inductive power transfer system in air (figure 3.21).

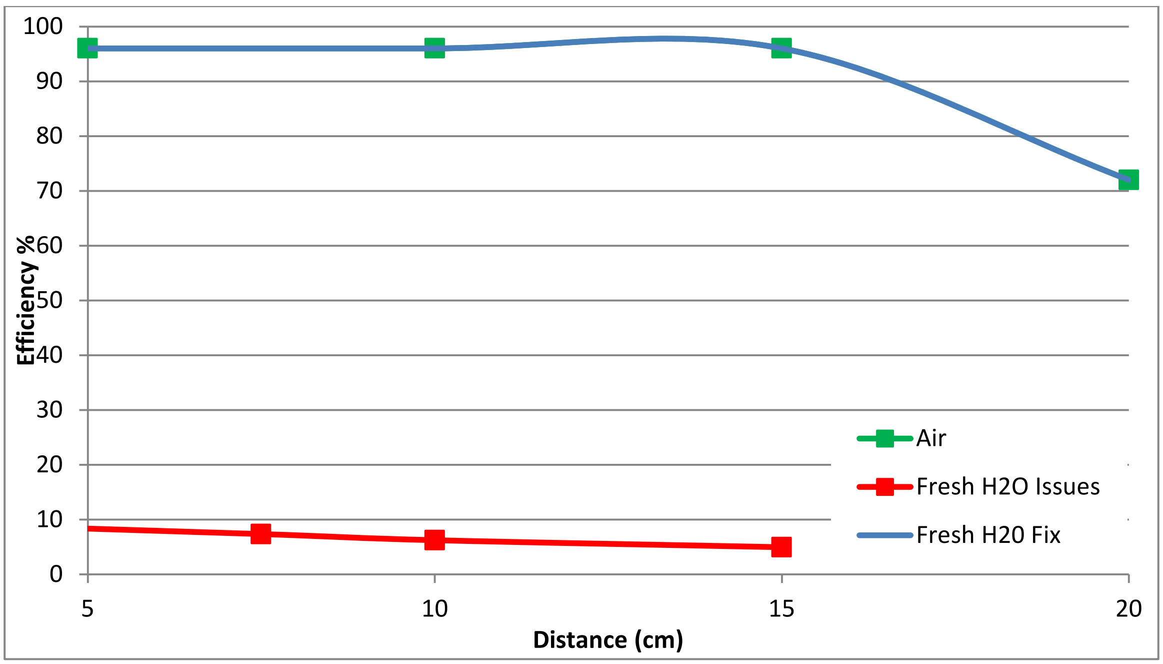

Figure 3.21 Freshwater vs Air Separation Effect Results

Next placing the coils in saltwater was examined. First there was the issue of placing the coils directly within the saltwater, which brought power transfer efficiency down significantly. Placing the coils in waterproof boxes brought the efficiency up while the coils are close together. The inductive power transfer system produces eddy currents within the saltwater. The eddy currents produce an opposing magnetic field that effects the efficiency of power transfer from the transmitter coil to the receiver coil. Figure 3.22 show compares in air power transfer efficiency results with original saltwater issues and compensated saltwater issues. While the compensation provides a better rate of power tranfer it is clear that as the transmitter and receiver are separated the greater the effect the eddy currents have upon the system.

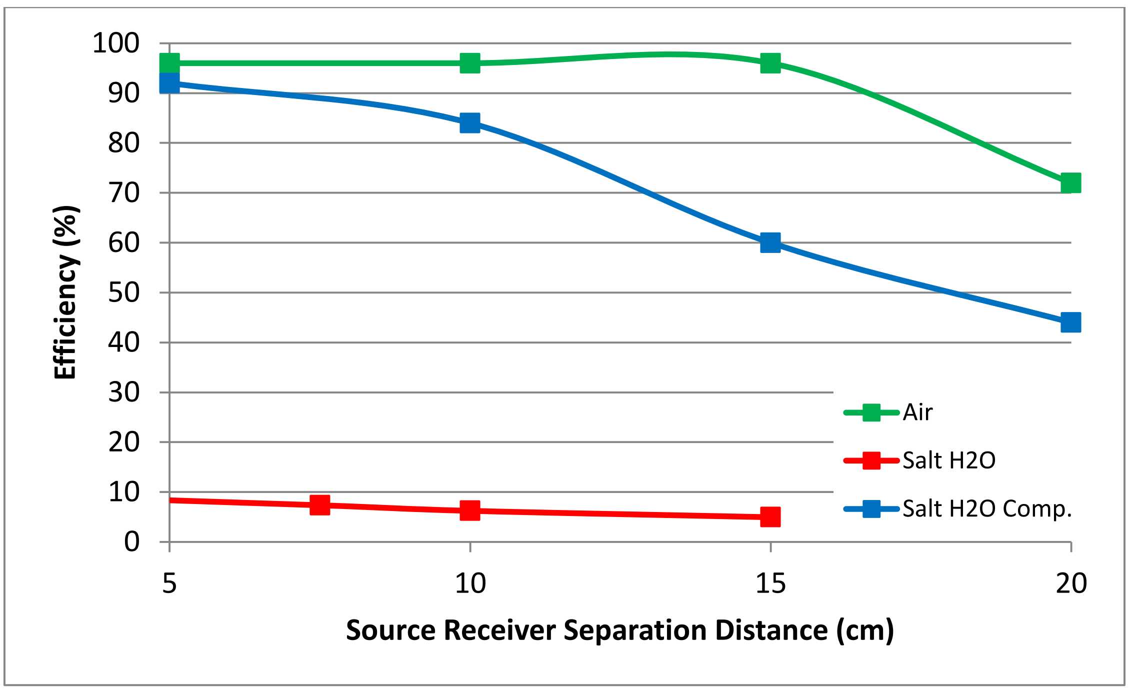

Figure 3.22 Saltwater vs Air Separation Effect Results

E. Coil Effect

2.9 Symmetric Ratio Coil Effect

Multiple coil winding ratios were used to see the effect on power transfer efficiency. The coils were all kept at the same diameter of 28cm and the system under test was symmetric. This means that the transmitting coil L_2 and receiving coil L_3 were exactly the same. The coils ratios under test were 1:1, 1:2, 1:3, 1:5, 1:10, and 1:20. In a typical set up using a ratio of 1:5 the transmitting side of the system would have 1 turn for L_1 and 5 turns for L_2. The receiving side of the system would have 5 turns for L_3 and 1 turn for L_4.

i. Coil Shift Tests

The system was tested by shifting the alignment of the receiver coils by 25% of the radius (7cm), but still touching the transmitting coils. All tests were performed under resonance since this is when maximum power transfer occurs. It was found for this system the maximum power transferred at resonance was very inefficient until a ratio of 1:5 (figure 3.22). The most efficient was 1:20, but the turns ratio of 1:10 has close to the same efficiency without the extra turns in the coil (figure 3.23). It is shown that as long as the Q-factor is kept high the system will show good efficiency in power transfer abilities.

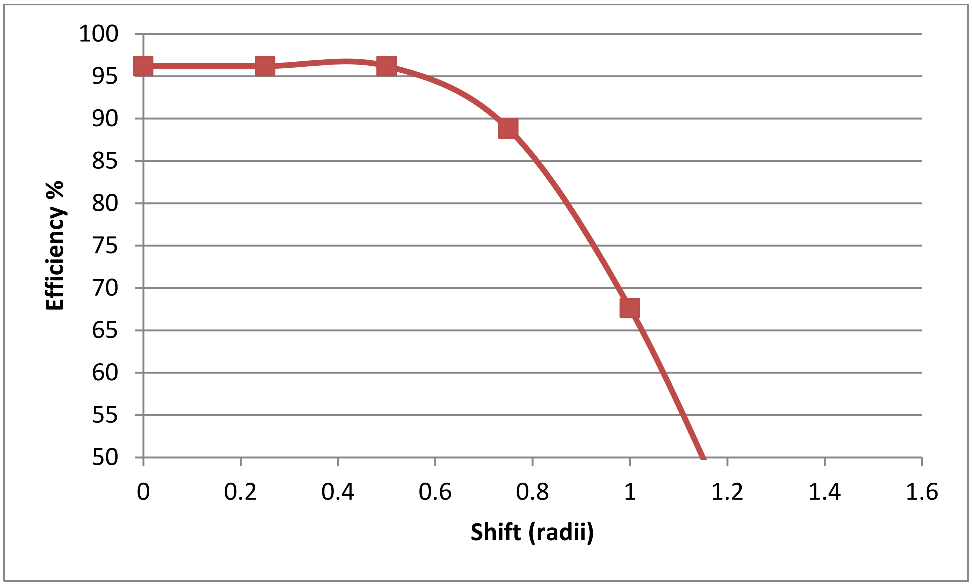

Figure 3.22 Efficiency vs Shift, Coil Ratio = 1:5

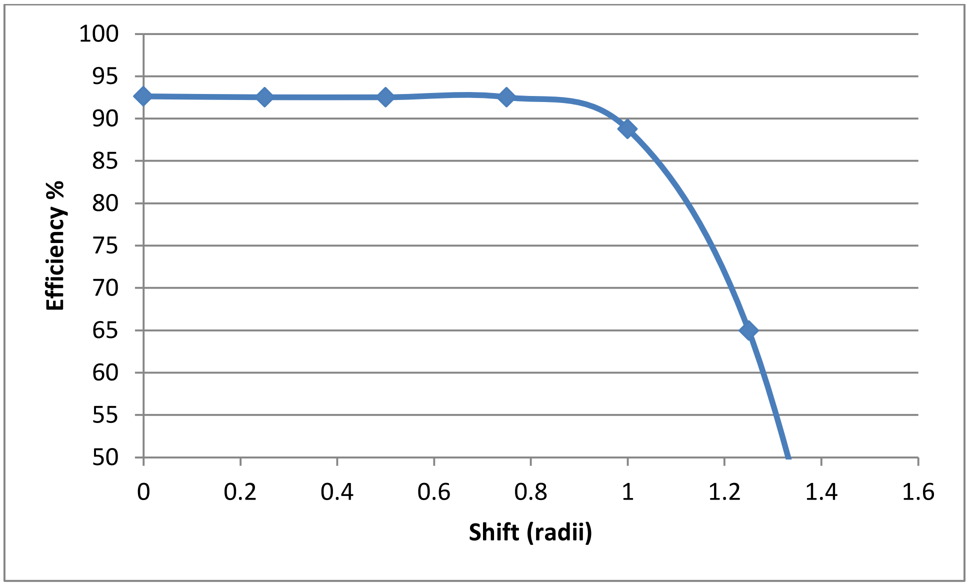

Figure 3.23 Efficiency vs Shift, Coil Ratio = 1:10

ii. Coil Shift + Separation Tests

Using the symmetric system with the best efficiency it is possible to now shift and separate the receiver coils and acceptable power transfer efficiencies. Again the ratio of 1:5

(figure 3.24) is less efficient then the ratio of 1:10 (figure 3.25).

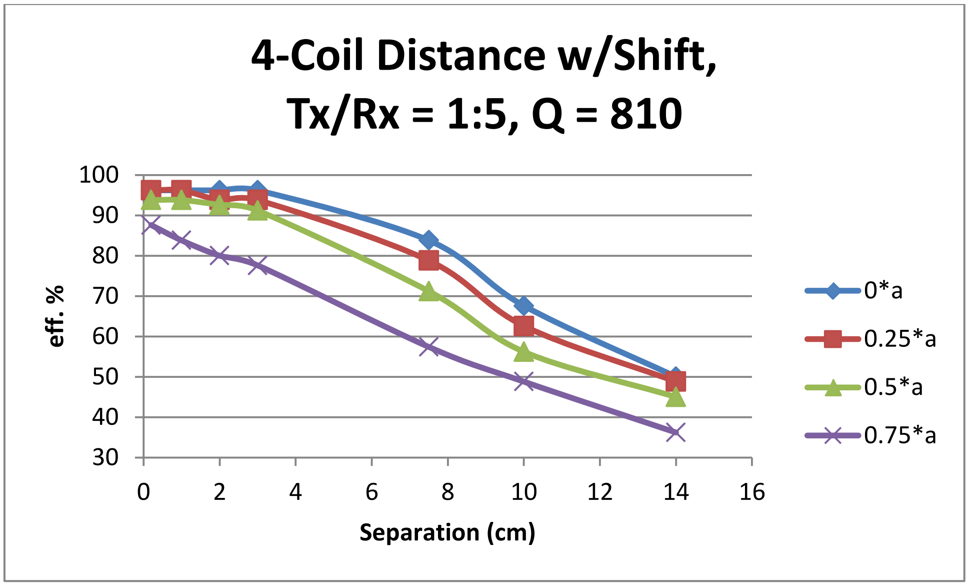

Figure 3.24 Efficiency vs Shift + Separation, Coil Ratio = 1:5

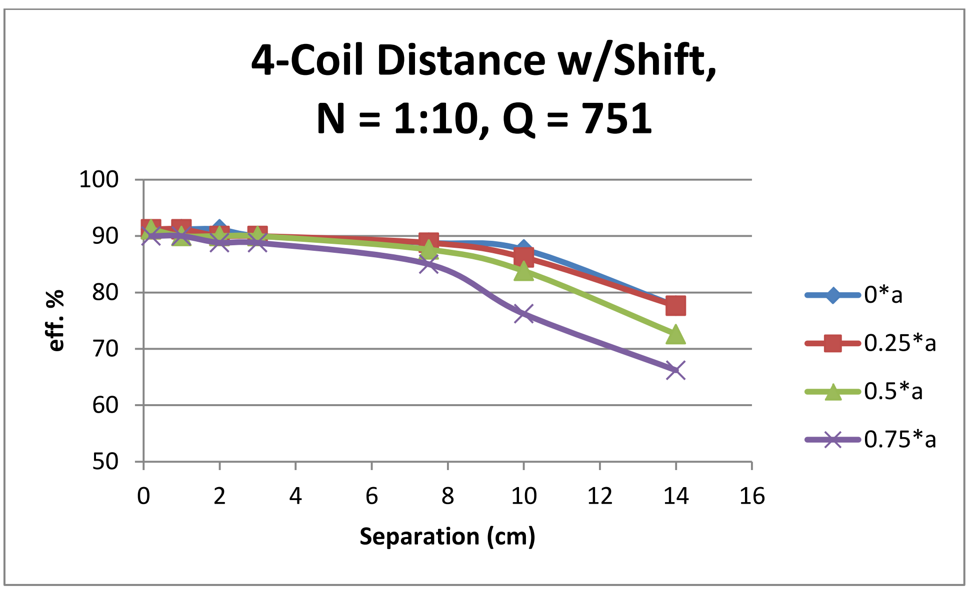

Figure 3.25 Efficiency vs Shift + Separation, Coil Ratio = 1:10

2.10 Asymmetric Coil Effect

The asymmetric tests were performed using the same coils and shift tests as in the symmetric experiment. The only difference in the tests were that instead of the transmitter and receiver coils being of equal turns the goal was to have a lower turns ratio for the receiver coils. This would decrease weight and materials at the receiver side of the system.

i. Coil Shift Tests

The shift tests were performed by keeping the transmitter ratio at 1:10 for all tests and varying the receiver ratio from 1:3 to 1:5. All results are compared to the optimal symmetrical system of 1:10. The results show that in the asymmetric system of Tx-1:10/Rx-1:3 (figure 3.26) and the asymmetric system of Tx-1:10/Rx-1:5 (figure 3.27) that the symmetric equivalent system is always better.

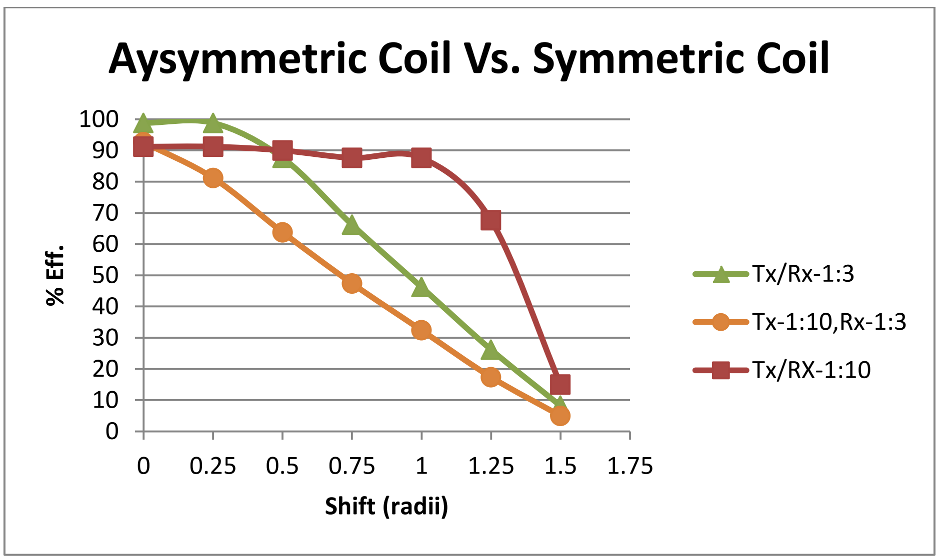

Figure 3.26 Asymmetric Coil Ratio Tx-1:10/Rx-1:3

The two figures compare the asymmetric coil ratio to both equivalent symmetric coil ratio tests. The optimal system is represented by the red line and is a symmetric system with a coil ratio of 1:10.

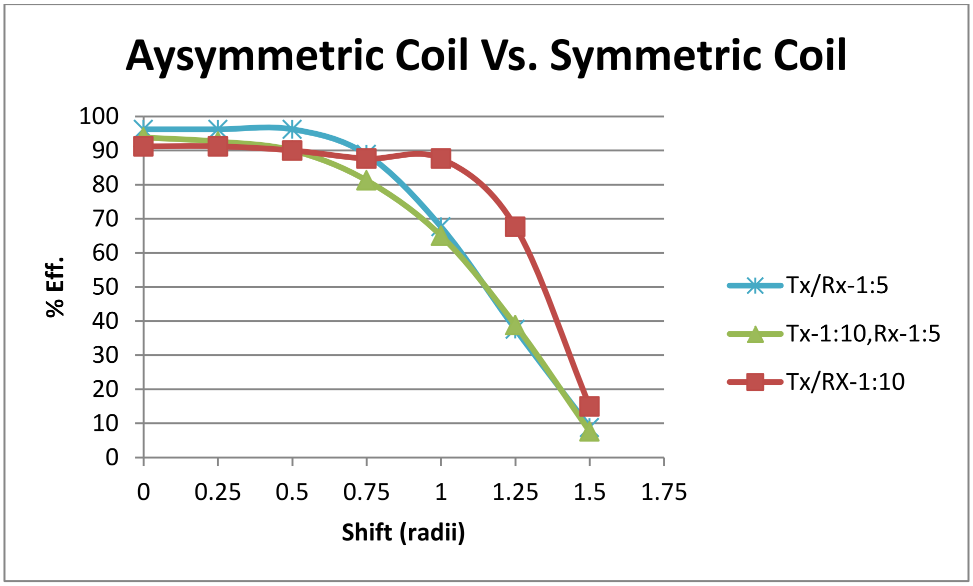

Figure 3.27 Asymmetric Coil Ratio Tx-1:10/Rx-1:5

2.11 Solid Wire versus Litz Wire

Skin effect in alternating current circuits causes the available cross-sectional area for current to flow in a conductor to decrease as frequency increases. This causes the effective resistance to increase since the cross-sectional area of the conductor decreases (Appendix D). Skin effect negatively affects the circuit since the Quality factor of a series circuit is inversely proportional to resistance.

Coil separation effect tests were performed on two sets of identical shape and number of turns coils with different wire type. The first set of coils constructed using #10 AWG solid magnet wire. The tests show (figure 3.28) that above 90% efficiency is possible, but the results diminish as the coils are further separated.

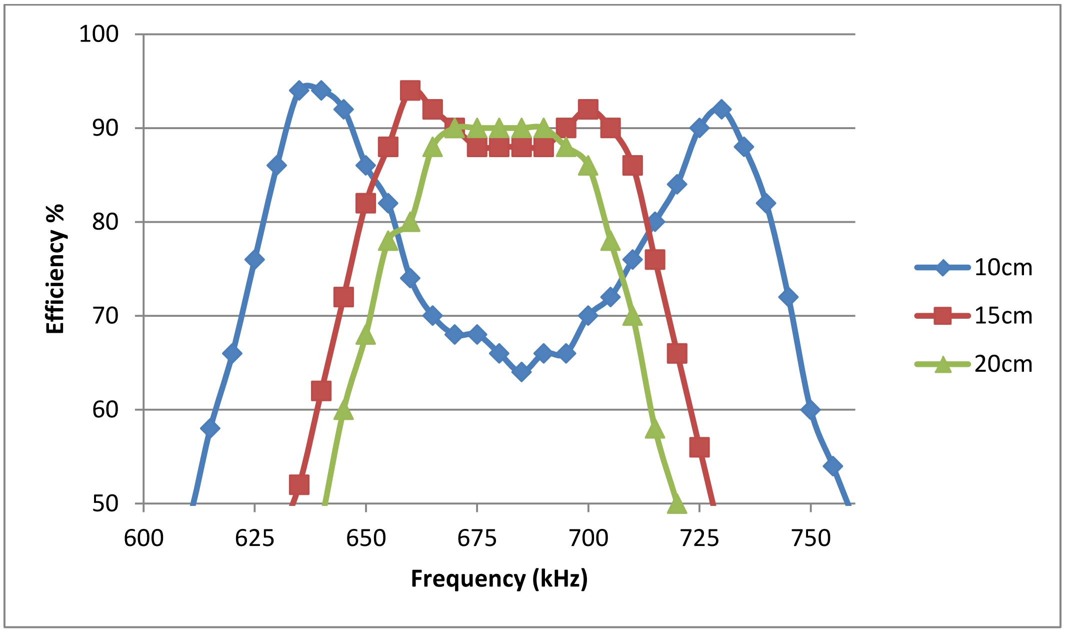

Figure 3.28 Solid Wire Frequency Sweeps

The second set of coils was constructed of Litz wire. Litz wire is made up of many twisted strands of wire that are of an equivalent size to that of the solid wire. This type of wire eliminates the skin effect due to high frequencies. The Litz wire tests are noticeably more efficient as the transmitting and receiving coils are separated from one another (figure 3.29).

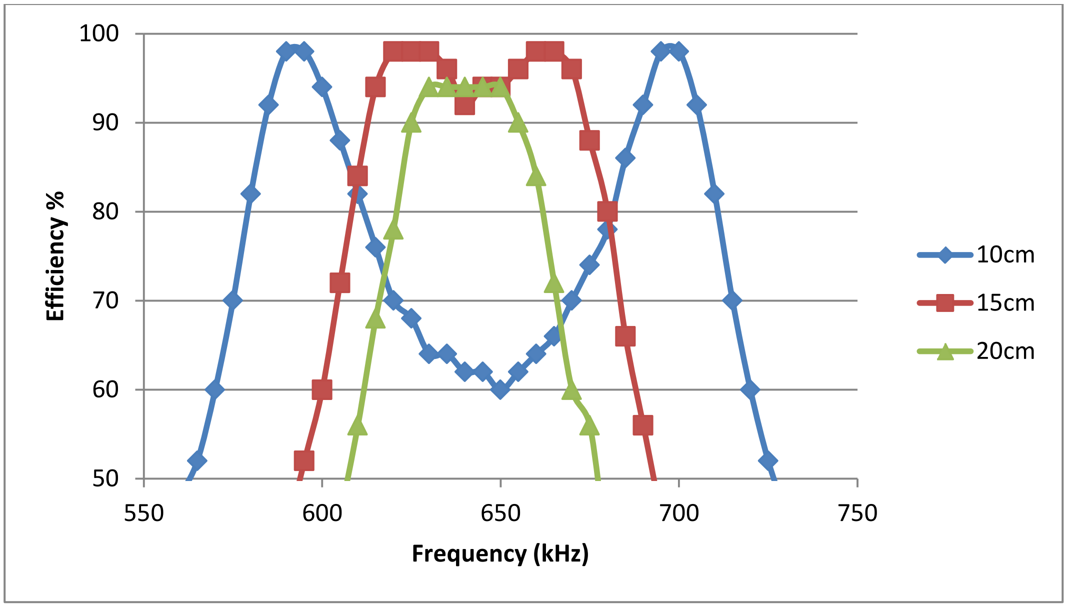

Figure 3.29 Litz Wire Frequency Sweeps

V. Future Research

Future research considerations will focus on optimization of highly resonant inductive power transfer systems in underwater test conditions. Now that there is an understanding on the systems capabilities in air the focus must shift to underwater applications. Optimization of design will include computer aided modeling of highly resonant inductive power transfer systems, as well as mathematical modeling. Another area of interest will be to focus on the use of Litz wire to increase power transfer efficiency. The biggest focus for optimization of power transfer efficiency will be on the use of Metamaterials. Metamaterials will be used to bend, focus, and increase the magnetic field produced by the inductive system.

The next area of research focus will be on increasing power transferred between the coils. The end goal is to use this system to inductively charge the battery system of an AUV. With that in mind higher power is required to charge large batteries in the kilowatt range quickly and efficiently.

The future is wide open for research and development of an underwater highly resonant inductive power transfer system. The AUV Laboratory at MIT Sea Grant is at the forefront of research in this area.

VI. Conclusion

Tests have shown that it is possible to achieve above 90% efficiency for a highly resonant wireless power transfer system. Tests have also shown that this is possible while the transmitting and receiving coils are separated further then the radius of the coils. Initial tests with circular coils in air were promising, while initial tests in water proved to be difficult. By applications of first principles the tests in fresh water have been brought to be equivalent to that in air. Salt water application to the highly resonant power transfer system is the end goal of the application. Tests have shown that salt water has shown degradation to the systems performance. Additional tests are being conducted to overcome the system degradation in saltwater.

Testing has also shown that for highly resonant power transfer systems Litz wire is preferable to solid wire and is required to keep system performance above 90%. Coil shape has been shown to provide an important benefit to the efficiency of the system as well. Coils that are the shape of an AUV (cigar shaped) provide the added benefit of extending the range of efficiency in charging coil shift tolerance to over three radii. All indications suggest that this shift tolerance can be further extended as well.

VII. References

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[2] E. Waffenschmidt and T. Staring, "Limitation of inductive power transfer for consumer applications," *13th European Conference on Power Electronics and Applications*, 2009, pp.1-10.

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[4] A. Kurs, A. Karalis, R. Moffatt, J.D. Joannopoulos, P. Fisher, and M. Soljacic, "Wireless Power Transfer via Strongly Coupled Magnetic Resonances," *Science*, vol. 317, no. 5834, pp.83-87, 2007.

[5] H.S. Kim, D.H. Won, B.J. Jang, "Simple design method of wireless power transfer system using 13.56MHz loop antennas," IEEE 978-1-4244-6392-3/10, pp. 1058-1063, 2010.

VIII. Appendix

Index: Appendix

1. 2-Coil Inductive Coupling Tests Results

The 2-coil self-resonant system was designed to show that power can be transferred wirelessly through the magnetic inductive coupling of a transmitter and receiver coil. The inductive system is basically an air cored transformer driven by a function generator. Both coils are circular loops of 10 turns and have a radius of 14cm. It was shown through the experimental results that this set up was highly inefficient when the transmitter and receiver coils were not axially aligned and touching each other (Figure 4.1).

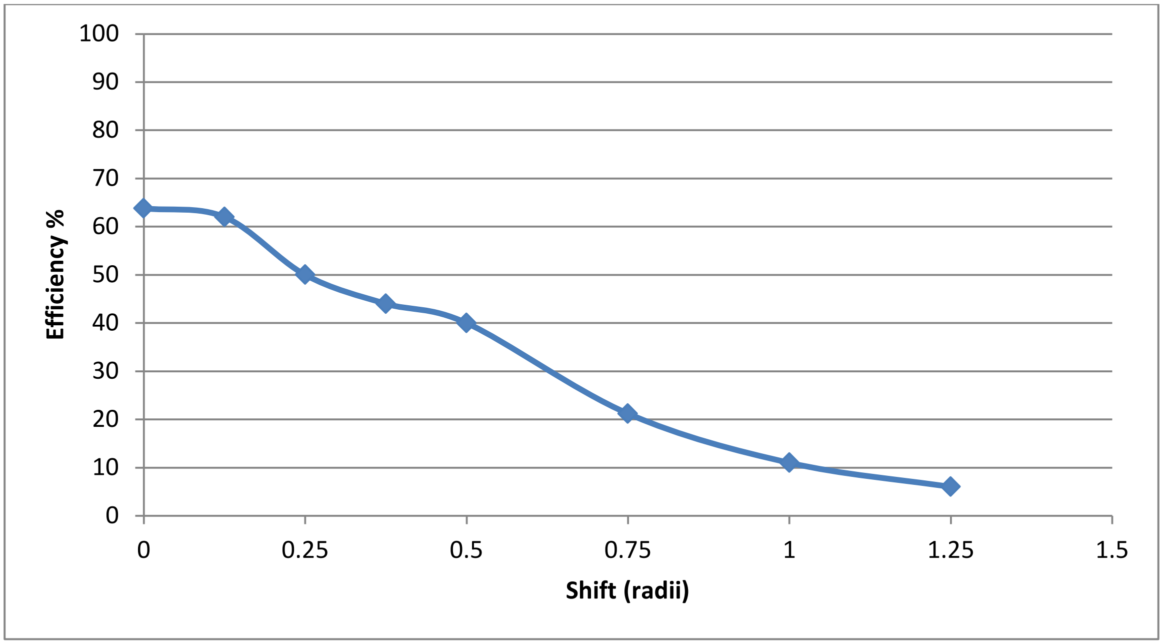

Figure 4.1 2-Coil Inductive Transfer Shift Effect

Inductive power coupling circuits based on parallel resonance are also examined. When this circuit is operating at its resonant frequency the impedance of the inductor and the capacitor cancel out and maximizes the power transferred to the purely resistive load. Using this circuit it is possible to get more power to the load then in the self-resonant circuit. This circuit also has a low coupling coefficient between the transmitting coil and receiving coil. Power transfer between the two coils drops just as fast as the self-resonant system (figure 4.2).

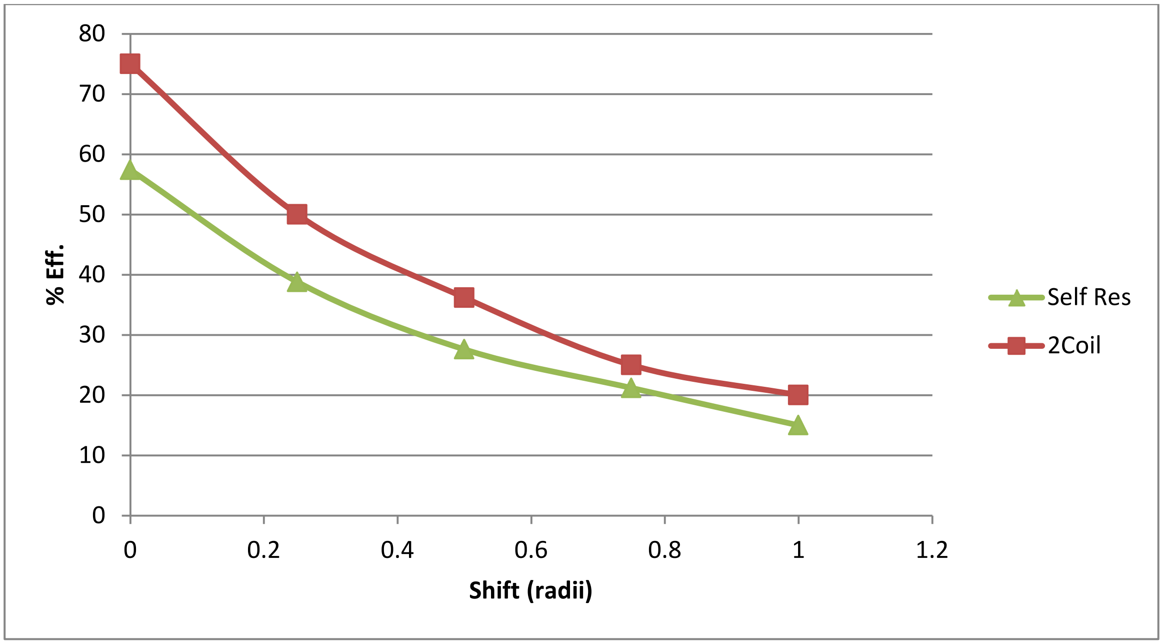

Figure 4.2 Efficiency of Self Resonant Vs. Added Resonance

The Q-factor in RLC circuits have been shown to increase the ability to transfer power between the coils of a resonant inductive power coupling system even with a low coupling coefficient between the two coils. Because R_S and R_L equal to 50Ω it is hard to get a Q-factor above 5.

i. **Receiver Coil 54% of the Transmitter Coil**

This test was designed to show the systems power transfer efficiencies based on a smaller receiver coil shifting in position to the stationary transmitter coil. The test was set up (figure 4.3) using the same transmitter coil from the previous tests, d = 28cm; N = 10; a = 14cm (L_2 radius), and a 54% smaller receiver coil, d = 15cm; N=10; b = 7.5cm (L_3 radius).

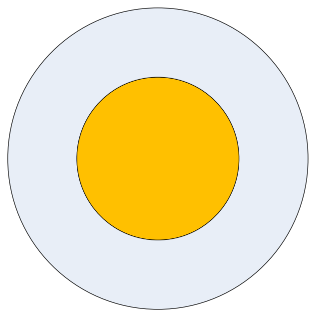

Figure 4.3 Receiver Coil Starting Point

The results show that as the receiver is shifted closer to the edges of the transmitting coil the efficiency of power goes up (figure 4.4).

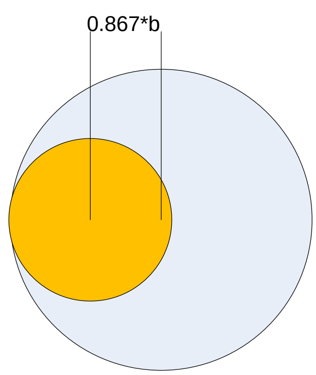

*Figure 4.4 Receiver Coil Max Power Shift = 0.867*b*

Figure 4.4 shows the orientation of the receiver compared to the transmitter for maximum power transfer efficiency for this system. When compared to the efficiency of power transferred from when the transmitter and receiver are of equal size and number of turns (blue line) it is clear that the system with the smaller receiver coil (red line) is not as efficient (figure 4.5).

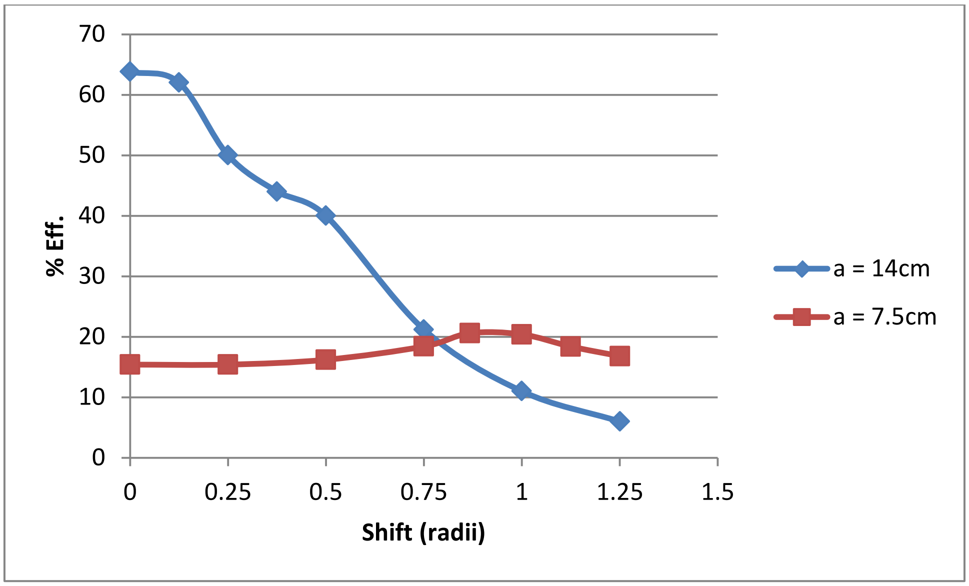

Figure 4.5 2-Coil Equal Transmitter and Receiver versus 54% Smaller Receiver Coil

2. Equations

ii. Maximum Power

Maximum power is calculated for an ideal transformer at resonance. While the circuit is in resonance the impedances of the inductor and the capacitor cancel out leaving a purely resistive circuit. Assuming that all the flux produced by the transmitter coil is absorbed by the receiver coil the circuit simplifies to a source with a source impedance and a load impedance (figure 4.6).

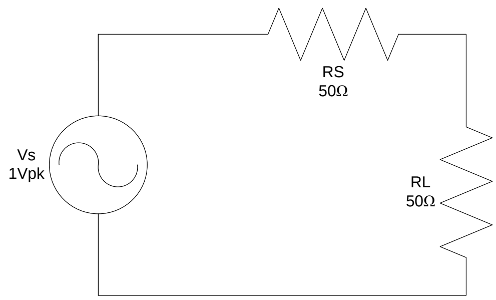

Figure 4.6 Simplified Ideal Transformer Circuit

Voltage at the load is equal to:

$$V_L = V_S \frac{R_L}{R_L + R_S} \qquad \text{Equation (4.1)}$$

Power at the load is equal to:

$$P_L = \frac{V_L^2}{R_L} \qquad \text{Equation (4.2)}$$

Substituting equation 4.1 into equation 4.2 and simplifying:

$$P_L = \left(\frac{R_L}{R_L + R_S} V_S\right)^2 \frac{1}{R_L} = \frac{{R_L}^2}{(R_L + R_S)^2} {V_S}^2 \frac{1}{R_L} = \frac{R_L^2 V_S^2}{R_S^2 + 2R_L R_S + R_L^2} \frac{1}{R_L} = \left(\frac{R_L V_S^2}{R_S^2 + 2R_L R_S + R_L^2}\right) \frac{R_L}{R_L} =$$

$$\frac{V_S^2}{\frac{R_S^2}{R_L} + 2R_S + R_L} \qquad \text{Equation (4.3)}$$

Setting $R_S = R_L$ gives the maximum power transfer of the system:

$$P_L = \frac{V_S^2}{4R_L} \qquad \text{Equation (4.4)}$$

iii. Skin Depth

Skin effect in resonant coils causes currents to flow towards the outside of the copper wires. The effective cross-sectional area of a solid coil is decreased such that the resistance of the coil increases. Resistance is determined by the major radius of the coil (a), the number of turns of the coil (N), copper conductivity (σ), the radius of the wire (r) and the source frequency.

$$R = \frac{aN}{\sigma r \delta}$$ Equation 4.5

$$\delta = \frac{1}{\sqrt{\pi f \mu_o \sigma}}$$ Equation 4.6

3. Figures

iv. Radius Reference

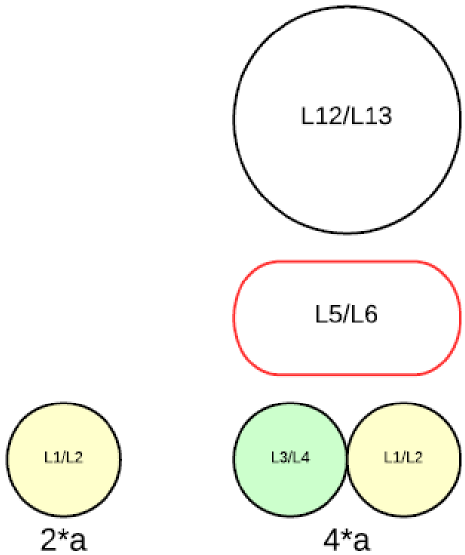

Figure 4.7 Radius Reference

v. Transmitter and Receiver Coil Equal

a) Two Transmitter Coils

The colors of the coils represent actively powered (connected to the power source) transmitter coils. It was found experimentally that the power transfer efficiency is significantly higher when the transmitter coil that is not optimally aligned to the receiver coil is shorted. The yellow transmitter coil represents the actively powered coil while the green transmitter coil represents the shorted out coil.

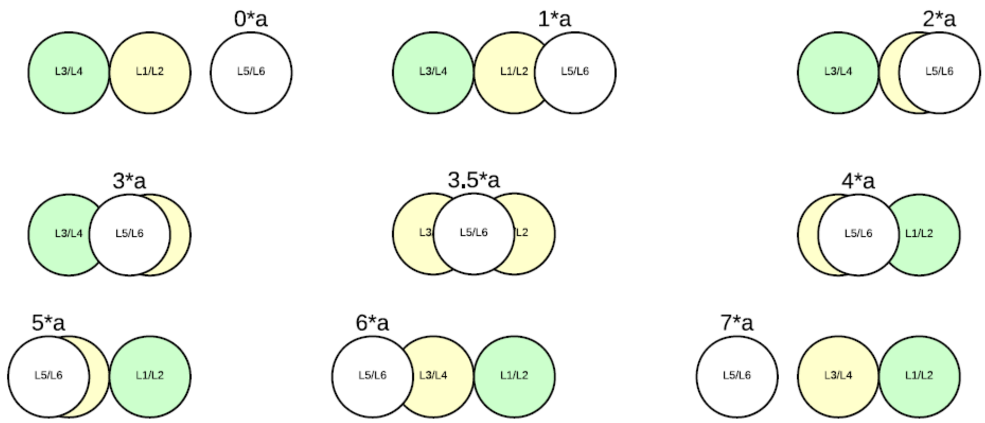

Figure 4.8 Two Transmitter Coils w/One Receiver Coil

b) Four Transmitter Coils

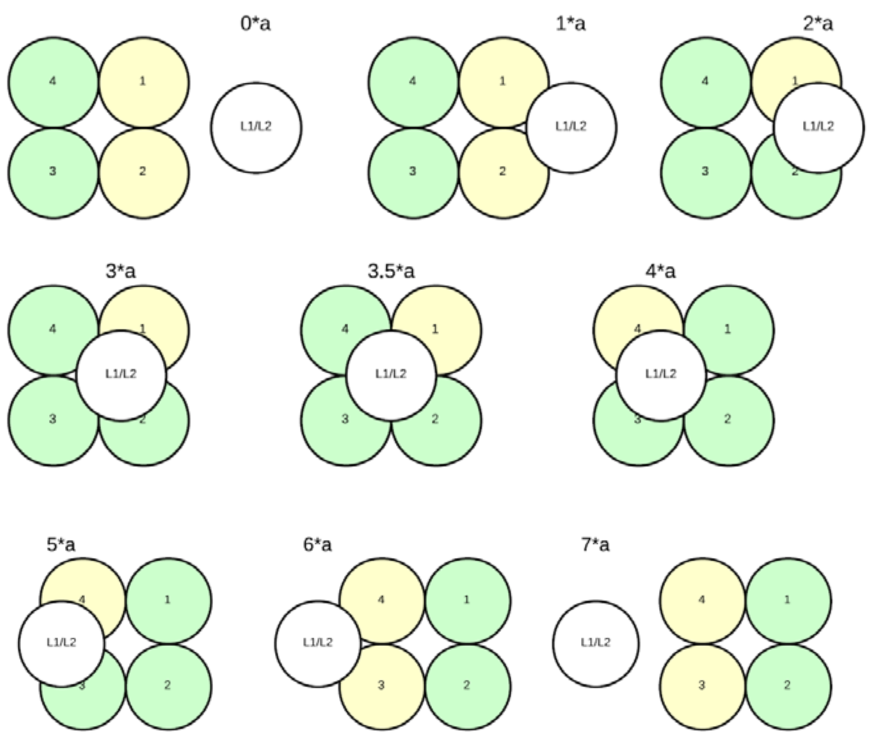

*Figure 4.9 Four Transmitter Coils (y-axis shift 0*a)*

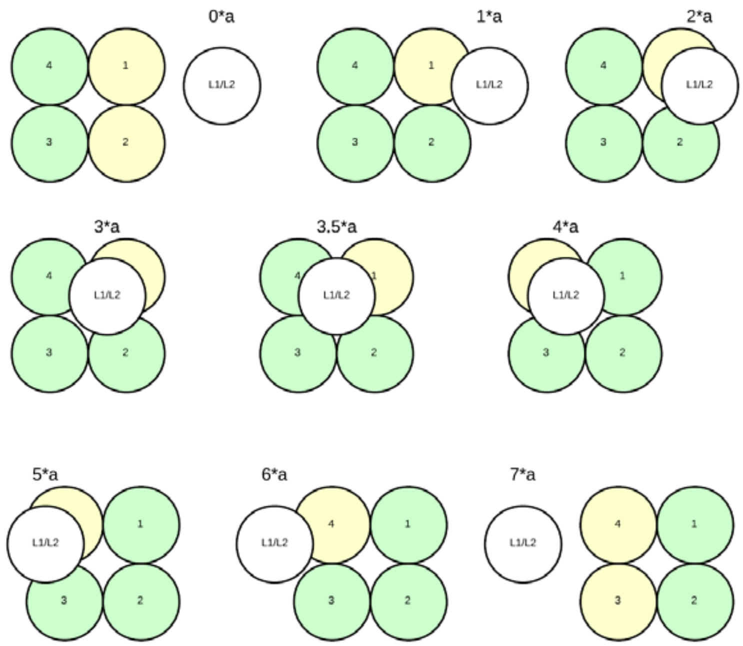

*Figure 4.10 Four Transmitter Coils (y-axis shift 0*a)*

vi. Transmitter Coil Circular with a Rounded Rectangular Receiver Coil

c) Two Transmitter Coils

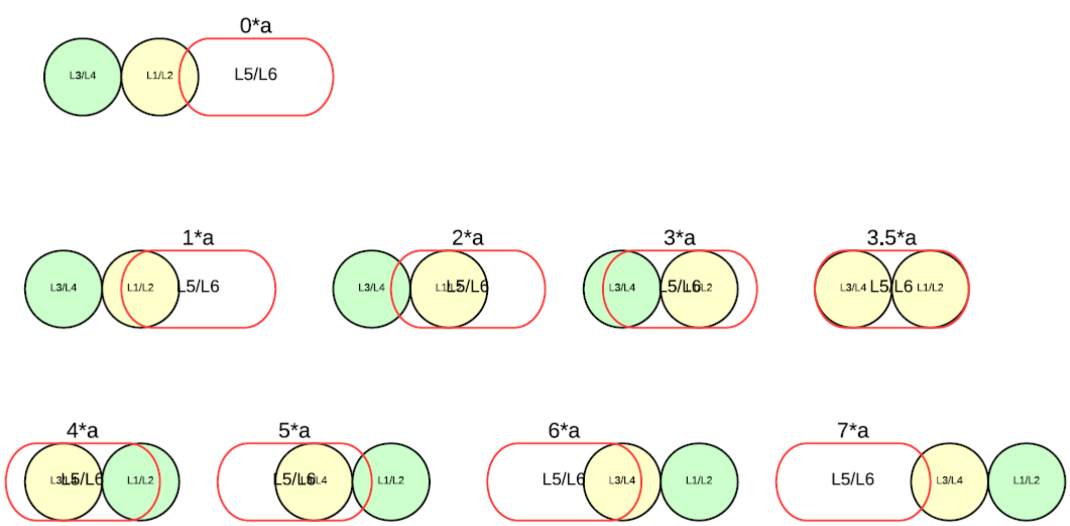

Figure 4.11 Two Transmitter Coils w/Rounded Rectangular Receiver

d) Four Transmitter Coils

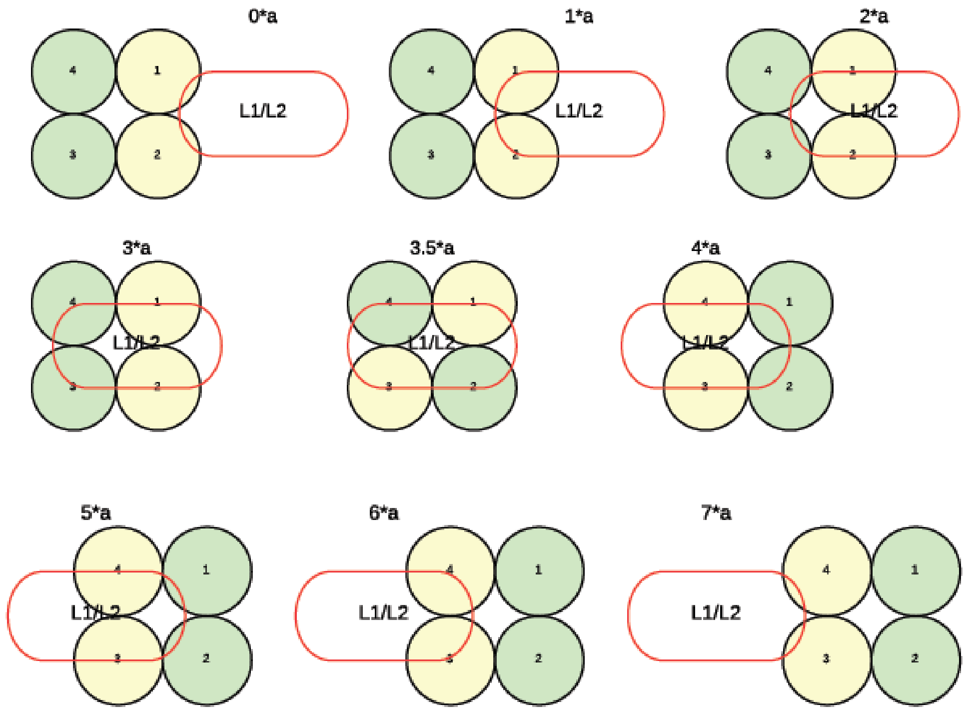

Figure 4.12 Four Transmitter Coils w/Rounded Rectangular Receiver

vii. Transmitter Coil 50% Smaller than Receiver Coil

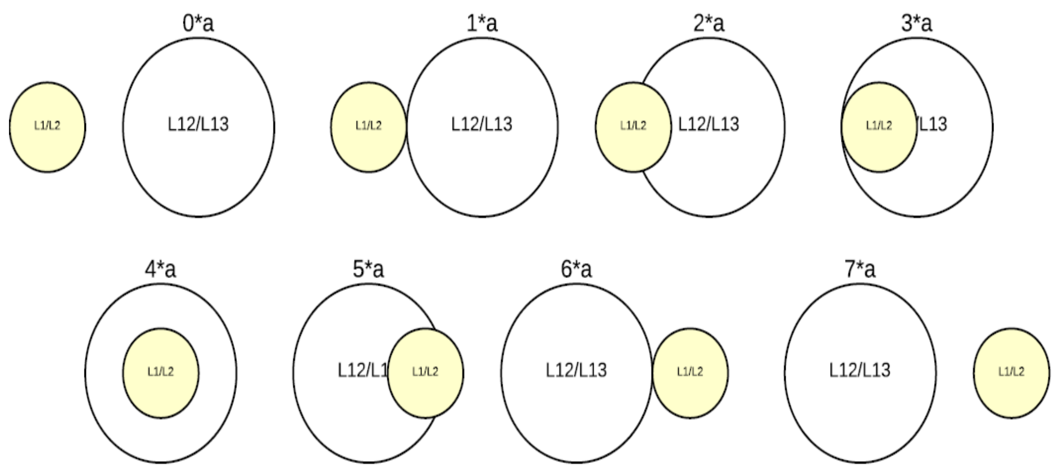

Figure 4.13 Transmitter Coil 50% Smaller than Receiver Coil