Auto-Adapting Circuit Topology for Efficient Wireless Power Transfer via Magnetic Resonances

An Undergraduate Thesis written by Johnathan Radcliff

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i. Abstract

As the world moves away from using wired connections to transmit data, wireless power transfer (WPT) offers another opportunity for “cutting the cord.” Technologies such as magnetic induction and radiative transmission already allow for energy to flow without a physical medium. However, these solutions are not without their limitations: magnetic induction’s short range keeps devices tethered to their charging docks, inhibiting mobility; radiative transfer is highly inefficient and has safety concerns due to high-energy radiofrequency exposure. Recently, WPT via magnetic resonance coupling has been proposed to replace these technologies in short-to-midrange applications due to its high efficiency and high-power throughput. Multitudes of research studies have proven its viability but fail to regard its implementation in real-world usage. In this paper, a wireless energy system is proposed that can automatically alter its circuit parameters as coil distance or alignment changes to maximize energy efficiency. Experimentation verifies this functionality and discovers a maximum end-to-end efficiency of 80.8% and an average operating efficiency of 68.7% over all distances between 0 and 1000 cm.

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1. Introduction to Wireless Power via Magnetic Resonances

1.1. The Problem

As mobile and embedded electronics become increasingly commonplace, the issue of charging and/or powering them becomes increasingly difficult. Most popular gadgets like cell phones and laptops do not have the energy capacity to last longer than a day, and that constant need to charge them places a burden on their users. Consumers can also struggle to navigate the incompatible charging standards between competing brands, leading to situations where they cannot charge their devices due to mismatched ports. They also may have difficulty comfortably using their device while it is charging due to an inconvenient outlet location or a short power cord. In parallel, embedded electronic devices such as security cameras, water/soil sensors for farmers, and smart thermostats can be difficult to power due to their location on a property. Even electric vehicles can struggle to get a consistent charge from a wire based on where they are parked. Popular answers to these issues often include purchasing a surplus of compatible charging cables as backups, longer charging cables for easier access to outlets, or costly wiring contracts to reach those remote devices.

However, these ideas do not address the source of the problem. At best, these measures are a slightly inconvenient insurance plan, but at their worst, they are an expensive and time-consuming venture. Additionally, they exacerbate the existing electronic waste problem plaguing the world right now [1]. If a solution is to address this problem, it must have three key features: it must be able to power devices at moderate distances, must be at least as convenient and accessible as any current options for charging, and cannot significantly contribute to the world's electronic waste.

1.2. Current Industry Solutions

In the last couple of decades, wireless power transfer has quickly risen in popularity given its widespread adoption in both consumer and commercial industries. It has become a hotspot of new research all aiming to improve its viability as a replacement for the wired conduction of electrical energy. There are two technologies commonly utilized for this purpose: inductive coupling and radiative transmission.

Inductive coupling is the most known amongst general consumers as it is the main tool advertised as wireless charging. It involves the placement of a device in need of charge on a pad containing a coil connected to power. The device has a coil inside itself as well, and when placed there, the coil in the pad induces a current inside the device’s coil which can be captured and used to charge its internal battery. Inductive coupling is a highly efficient method of charging and has applications in cellular electronics, personal hygiene products, and even some electric vehicles [2] [3].

Radiative transfer is the process by which an antenna transmits electromagnetic radiation over a carrier signal which can be captured by one or more receiver antennae for rectification and storage. It is designed to work over long distances and transmit considerable amounts of energy [4]. For this reason, it is used to power devices that cannot be reached by the existing electrical grid. Able to transmit kilowatts of power over the span of several kilometers, this technology is essential for a multitude of situations, such as providing energy to an isolated site or ensuring that the energy requirements of remote electrical devices are met.

However, these solutions are not without their problems. Inductive coupling has a short operating range (<5cm) outside of which the efficiency drops significantly; alignment of the coils also greatly impacts the effectiveness of this method. Because of that limitation, most devices, while technically charging without a physical cord inserted into them, are tethered to a wire anyway. Radiative transfer has faults in its design philosophy as well. It operates at an exceptionally low efficiency due to the low conductance of the medium the energy is propagated through [5]. Because of these losses, most transmitters must output a very large amount of power to compensate for the subpar efficiency, which many government and health organizations fear could lead to health problems [5] [6].

1.3. Proposal of a New System and Its Benefits

Enter: magnetic resonance wireless power transfer. This is a mechanism that uses magnetic fields to generate an acoustic-like “resonance” effect to transmit energy [7]. Like the phenomenon that causes a glass cup to shatter when an opera singer belts a specific note, magnetic fields generated by coils can have resonant frequencies that cause energy to transfer from one field to another. This has shown to be not only a highly efficient method of energy transmission comparable to inductive coupling, but also effective over ranges exceeding two meters, bridging the gap in performance between inductive and radiative transfer technologies [7] [8].

After its conception in 2007, researchers have studied its effects to make magnetic resonances more viable for real-world use. Analysis of each aspect of the design of these structures has been studied in detail, and potential improvements have been discovered. Recently, much work has been done on enhancing the performance of the magnetic resonances as they work in systems with dynamic elements, such as changing spans between the coils, alignment, or output power [9] [10]. These studies have shown that it is possible to implement correcting mechanisms into the approach and that these approaches provide a non-negligible impact on power throughput and efficiency. If applied all together, the magnetically resonant coils could adapt to a diverse set of operating conditions automatically, aiding in the ease and usability of this system.

In this study, a structure is created that can make continuous, self-correcting adjustments to its circuitry and can provide consistent power at high efficiency at all transmission distances up to one meter. It will do this by actively tuning the impedance matching network for the transmission line in the coils and the rectification rate of the received power going to the system load. The benefits of this system should include higher overall energy transfer efficiency to a system with only one or none of these modifications. The architecture should demonstrate should it encounter a real-world scenario wherein devices change alignment or distance from the transmitter randomly that it can adapt itself to maximize power throughput, as necessary.

2. Historical and Background Analysis of the Art

2.1. Origins and Early History

Since the late 19th century, the transfer of electrical energy over electromagnetic waves has been sought after to reduce the need for wires to power electrical devices. This concept reduces the cost of maintaining a physical connection, and its potential flexibility benefits mobile and difficult-to-access electrical systems. Nikola Tesla, one of the first major proponents of this idea, worked to create a long-distance power delivery scheme using omnidirectional electromagnetic coupling between two coils which, in his view, would not only provide free energy to all but also help resolve energy-related conflicts between nations [11] [12]. However, as we now know, these efforts were not fruitful, and while the experiments did aid the development of long-distance wireless communication, wireless power transfer could not be achieved [11].

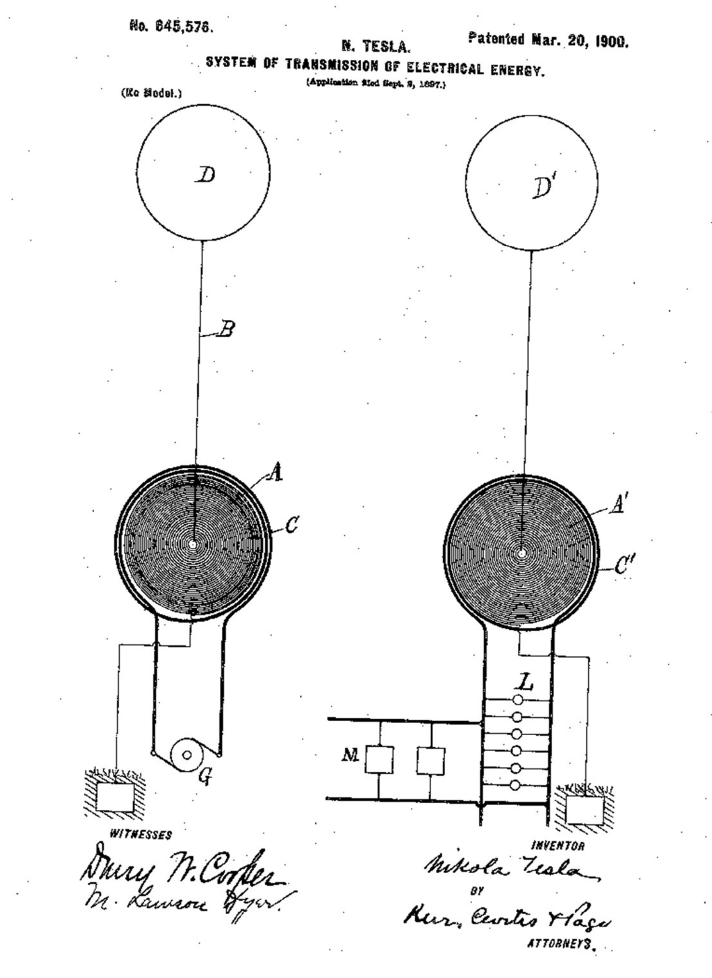

Figure 1: The patent art for Tesla's system of electrical energy transmission [12]

However, despite its initial failures, scientists and engineers have since made meaningful progress pursuance of wireless power. With the development of microwave technology in World War II, William C. Brown invented the rectenna, a device that could efficiently convert microwaves to DC power, which he then used to transmit power over distances upwards of 1.5 km at around 50% efficiency [13]. In the early 1960s, scientists at the University of Missouri created the transcutaneous energy transformer (TET), a near-field highly efficient system that uses inductive coupling between two coils for powering implanted medical devices [14]. With these and other developments, the technology has matured significantly, providing the possibility that we can achieve a wireless future just as Tesla imagined.

2.2. Industry Applications

2.2.1. Solar Energy Collection

Electromagnetic power transmission, aided by the research conducted throughout the 19th and 20th centuries, has potential as a mechanism for the long-range transfer of solar energy collected from space as a supplement to existing energy generation. As noted, the invention of the rectenna opened the door for far-field transmission schemes, wherein considerable amounts of electricity could be sent from one location to another in the form of electromagnetic radiation. A team run by Peter E. Glaser in the late 1960s sought to create the first solar power delivery system, in which a satellite orbiting the Earth would harvest massive amounts of solar energy and beam it to the surface using lasers [15].

However, only recently have countries around the world made significant steps towards the practical implementation of such systems. Since 2000, the Japanese scientific community has been developing two similar solar power satellites (SPS), one from the Japanese Aerospace

Exploration Agency and the other from the Ministry of Economy, Trade, and Industry. These stations will orbit in Geostationary Earth Orbit, have a large array of solar collectors and panels to collect energy, and convert the energy to microwaves to then transmit it to the surface [16]. In the United States, the US Naval Research Laboratory began testing its SPS designs in 2020 and the California Institute of Technology plans to launch a test array of space-based solar panels in 2023 [17] [18]. While not yet implemented, this system has enormous potential for clean and efficient energy production which warrants its continued study.

2.2.2. Consumer Electronics

One field where remote power delivery has been implemented successfully is consumer electronics. From hygienic products such as toothbrushes and razors to personal cellular phones, the practical benefits of a wireless power connection have made their mark on the design of user-facing products. These devices often use inductive charging, a two-coil system in which a transmitter coil induces an alternating current into the receiver coil. The alternating current from the receiver is rectified into a direct current usable for the rest of the electrical components in the system [2]. Since its widespread adoption, large cellular and electronics companies have developed a common specification called Qi, aiming to standardize inductive charging procedures across a variety of platforms to ensure that each device utilizing it has maximum interoperability with other devices that have also adopted it.

Personal electronic devices typically do not require the high-power capability that the long-range power delivery solutions offer with most only requiring 5 – 15W of power over a brief operating time. However, progress is being made to charge higher-wattage devices such as laptops and tablets, requiring anywhere from 10 – 100 W of charging capability depending on its size and computational ability [19]. Consumer electronics is one of the most notable places where wireless power has been successful, and its widespread adoption means that continued research into the topic will surely continue.

2.2.3. Robotics and Automobiles

Another area that has utilized electromagnetic power transmission is the industrial sector, particularly the robotics and automotive fields. The city of Detroit has awarded $1.9 million to Electreon, a company that places wireless charging coils into roads and highways. Combined with above and below-ground management units, the technology allows electric trucks and cars to charge while operating, improving range significantly [20]. Both Kansas and Washington have begun plans for doing similar operations with metro and airport buses, putting the coils under places where they may idle such as bus stops and loading docks [21] [22]. This method of gradual, intermittent charging keeps the vehicles charged above 90% after a full day of operation, reduces the amount of energy required to charge the buses after hours, and minimizes strain on the grid at peak times [22].

Consumer cars are going to benefit from this technology as well, as multiple vehicle manufacturers have begun developing and installing wireless charging transmission systems into their products. Volvo has begun tests in Sweden to develop a fast wireless charging taxi service throughout the city of Gothenburg by placing these power stations underneath the pavement as well, allowing for the vehicles to charge from 20% - 80% battery capacity in a little over an hour [23]. BMW, Nissan, and Volkswagen have all built concept and pre-production cars that utilize the technology, but they are continuing to solve the cost and efficiency problems before they can be mass-produced [3].

Finally, in the field of robotics, companies, and universities have developed systems for inductive and RF charging at a distance. The Georgia Institute of Technology has applied the technology to its Robotarium, a facility where students and faculty can study swarm behavior in robots powered by wireless charging stations [24]. As these institutions continue to adopt wireless power transfer schemes to their products or research, the technology will mature further, allowing for even more adoption and growth in popularity which brings a wireless future closer to the present.

2.3. Description of Various Forms of Wireless Power Transfer

2.3.1. Radiofrequency Transfer

Having discussed areas in which wireless power has been applied, it is important to discuss the underlying physics on which the technology works. First, we will cover radiofrequency (RF) wireless power transfer. This technique utilizes high-frequency electromagnetic waves that carry substantial amounts of energy over exceptionally long distances, upwards of tens to hundreds of kilometers [4] [17]. The dominant carrier of the power is microwave radiation whose operating frequencies can range from upper MHz range to well into the tens of GHz, although certain instances involve using laser optics as a medium for transmission. It can transmit well over 1kW of power and in certain cases reach power levels as high as +10kW [25] [15]. The technology suffers from low efficiencies, especially at longer distances, meaning the transmitter needs to emit more power to meet the required load at the receiver. Unfortunately, this increased output can cause health problems in living tissue in humans and animals which government and regulatory bodies are aware of [5] [6]. As a result, companies intending on using this technique to transmit power must either be able to prove its safety amongst a general human population or ensure that humans are outside of its operating range. In brief, radiative charging, while a useful system for carrying considerable amounts of power over long distances, currently fails to meet the efficiency and safety requirements necessary for its widespread adoption.

2.3.2. Inductive Coupling

The other (and more common) mode of wireless power comes in the form of inductive charging, where two coils induce a magnetic field between each other to transfer energy between themselves. This technology is a high-efficiency system, with theoretical efficiencies up to 90% and actual efficiencies closer to surpassing 80% [2] [5]. It is also capable of low and high-energy transmission, with Qi charging staying in the 5-15W range and automotive standards reaching up to 40kW of power [19] [23]. The phenomenon is a well-understood area of physics as well, as induction has been studied since Michael Faraday discovered the concept in the early 19th century. The coils, however, must be close to each other, losing effectiveness at energy transmission when the distances between the transmitter and receiver exceed 5cm [2] [5]. This system also works well with varying load levels, being able to quickly adapt the throughput of power to match the need on demand. If the maximum distance could be expanded, induction could serve as the optimal combination of efficiency, adaptability, and range of operation.

2.3.3. Magnetic Resonances

As shown above, each of these solutions has benefits and drawbacks when serving power to electrical devices. Whether the problem is efficiency, maximum operating range, or output power, there exists a gap in this field that neither EM radiation nor inductance charging can address directly. To address this problem, a group of MIT professors began studying a phenomenon known as magnetic resonance, a mechanism that uses coils of wire to generate magnetic fields that can resonate to transmit energy [7]. This scheme can provide efficiencies of up to 80% at distances well above the threshold of inductance charging while also being capable of delivering the wattages normal to radiofrequency transmission techniques [8].

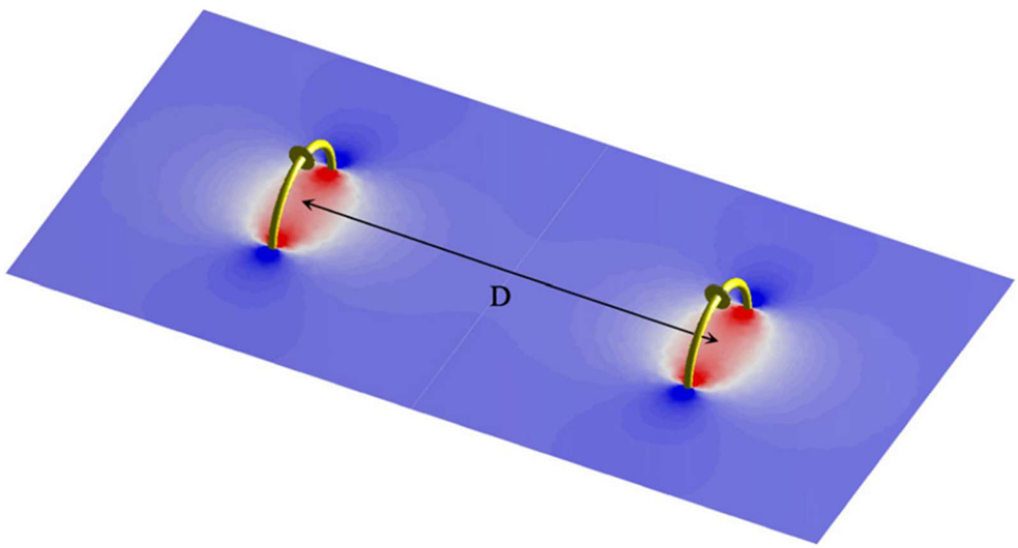

Figure 2: A simulated render of two coils resonating with each other at a distance D [7]

Acknowledging this feature, it has the potential to outperform the other remote energy transfer systems in terms of practical benefit and electrical cost savings. Researchers have shown that with accommodations it can be more efficient than both inductive and RF-based charging methods [5] [25]. Its range dwarfs inductive charging systems, and at equivalent distances, the power efficiency of magnetically resonant devices is orders of magnitude higher than that of RF transmission [26]. However, this technology still needs further development to achieve real-world viability. Over its entire range, the average end-to-end efficiency of the basic system is less than 60% [27]. Moreover, while its range is greater than the competing technologies, magnetically resonant energy transfer struggles to consistently provide power past two meters [8]. Replacing wires will require the efficiency of magnetic resonances to be above 80% across its entire operational range, which itself needs to extend to at least one meter for most mid-range applications.

3. The State of the Art of Magnetic Resonances

3.1. System Architecture

There exist a multitude of options concerning the construction of magnetically resonant circuits for wireless power transfer. These schemes vary in size, complexity, and efficiency, providing pros and cons that guide engineers to create systems that best fit their circumstances. Included below are examples and descriptions of two, four, and many-coiled mechanisms for energy transmission.

3.1.1. Two-Coil Systems

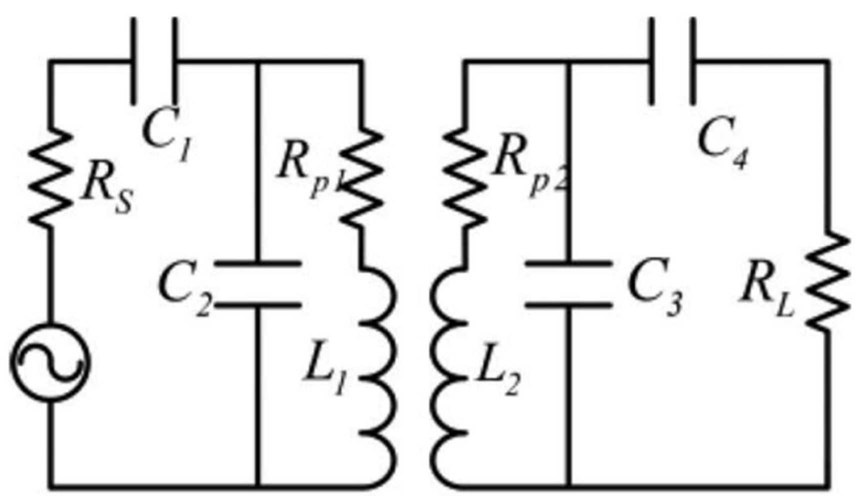

Figure 3: Circuit equivalent of a 2-coil power transfer scheme [28]

The two-coiled design, a circuit equivalent of which is shown in Figure 3, is the simplest design for the implementation of wireless power transfer. Consisting solely of a transmission and receiver coil for energy propagation, each coil is directly connected to either the energy source or system load and must move in conjunction with that element. Due to its simplicity, this option is most widely used and referred to when utilizing or discussing magnetic resonance technology. This system by nature requires on average less engineering time, materials, and space which makes it ideal for applications where there is limited space or quick development is essential. However, this minimalism is not without its problems; because the coils are directly attached to the voltage source and load and have no intermediary, there exists the potential for unnecessary losses as the coils are directly susceptible to any signal noise or voltage anomalies [6]. Furthermore, the system is much more susceptible to efficiency loss when used at distances much greater than the radius of the coil than the other architectures [8].

3.1.2. Four-Coil Systems

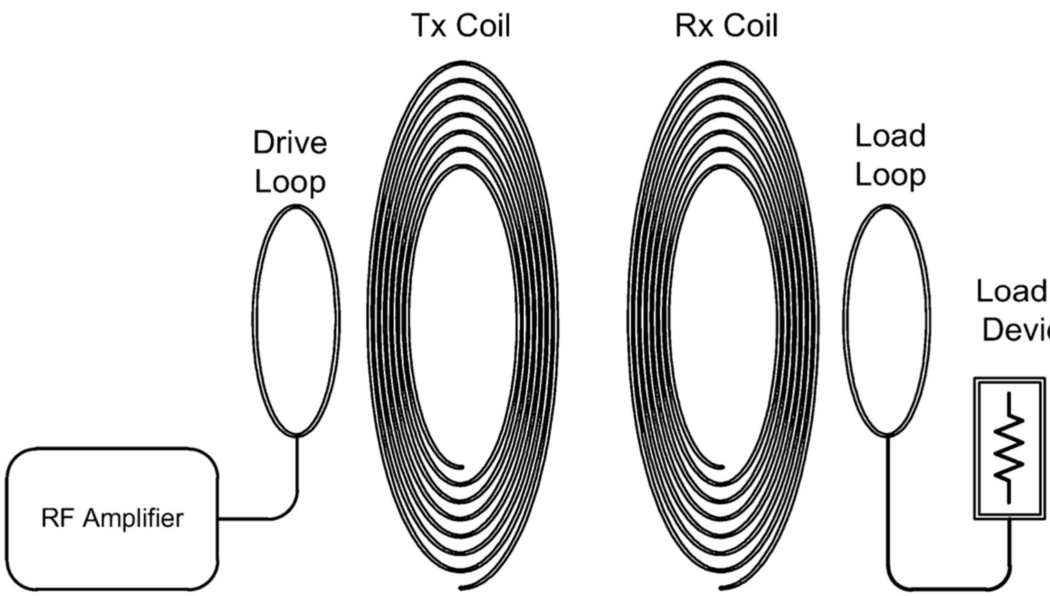

Figure 4: A four-coiled WPT system [29]

As opposed to the two-coil system, four-coil systems use two intermediary coils to exchange the energy in the system. Though the two-coil system is more common, this was the architecture described by the MIT team when they first proposed utilizing magnetic resonances for energy transfer [7]. As shown in Figure 4, the system driver and load are connected to loops that resonate with the larger, multi-turn spirals that generate the magnetic fields and move between each other. To ensure the loops match the resonant frequency of the transfer coils, external capacitors and inductors must be added otherwise the system will experience heavy inductive losses, lowering efficiency [6].

There exist numerous benefits and challenges to this architecture that must be considered when designing a wireless power system. This solution is better suited for high-efficiency and high-power solutions as the spirals can be much larger than the driver loops [26].

In addition, the fact the transfer coils are disconnected from the main circuit isolates them from any noise or power level irregularities and allows for more reliable performance. This disconnection also allows for additional degrees of freedom in impedance matching: aligning coils and shifting the distance between them is much easier [6]. Due to the extra elements, however, complexity is increased, and assumptions that can be made when modeling two-coil systems are not afforded when four coils are used due to the nontrivial physics involved [26]. Finally, the layout of these components takes up more space which means certain applications that require smaller designs are not as easily solved with this approach [6].

3.1.3. Domino Resonator (Many-Coiled) Systems

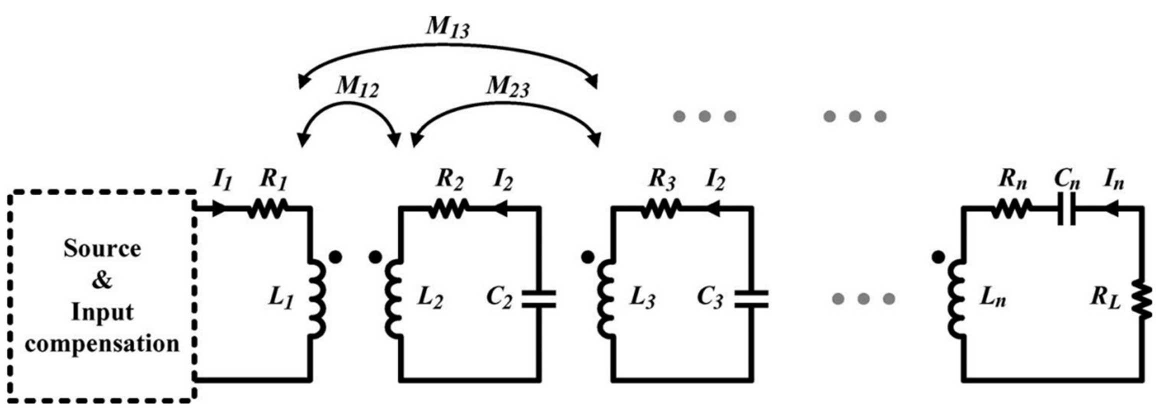

Figure 5: Schematic of n *domino resonators [30]*

The domino resonator structure involves using multiple strongly coupled magnetic resonators to transfer energy across much farther distances than a single pair of coils could with minimal losses to energy efficiency and power throughput. Figure 5 shows a rudimentary schematic diagram of its operation. It shows power generation and the transmitter resonator, each intermediate coil represented as a resonant LRC circuit, current flow in each of these resonators, and the effect of mutual inductance between neighboring and non-neighboring coils. This structure is meant to address the problem that resonators have when attempting to transmit power over distances orders of magnitude greater than the coil diameter. If proper considerations are made to operating frequency and distance between each resonator, efficiency will see minimal negative impact [30].

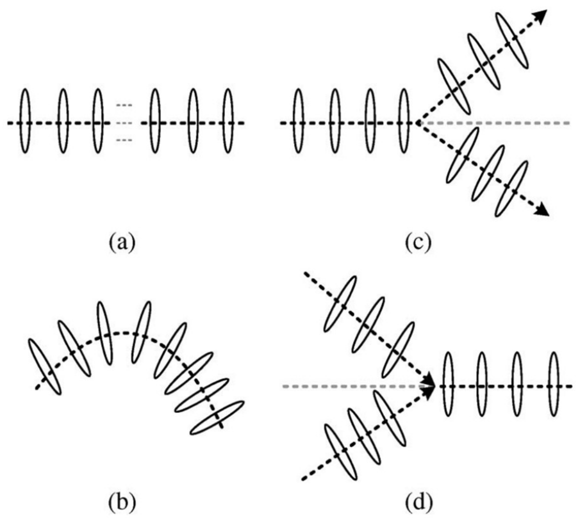

Figure 6: Drawings of how domino resonators can direct power [30]

One interesting benefit of the domino resonator approach is that the direction of energy flow can be determined by the orientation of each of the coils. Energy can be moved along curves, around tight angles, and even in a circular motion [6]. This phenomenon gives engineers the ability to target specific devices or areas of devices when creating these wireless power systems. In addition, these energy flows can be combined to increase power or split in two directions as needed as shown in Figure 6. There are significant design considerations to be made for changing the angle of energy flow; size and physical complexity will also increase rapidly as each new coil is added. Despite this, this option is suitable for circumstances where power needs to be transmitted over long distances without using standard wired conductors [30].

3.2. Coils

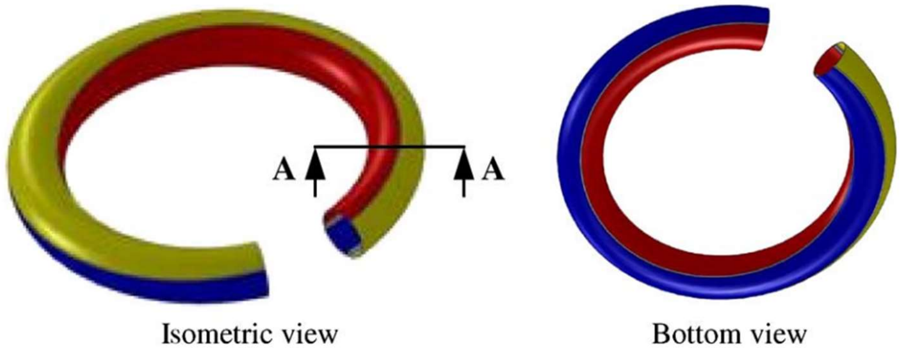

Figure 7: Render of a surface spiral layout on a coil [31]

Coil construction and design are critical to any wireless power system due to their direct connection to system performance and functionality. Size has a direct connection to the range of operation; efficiency drops off as a function of the ratio of the total distance between the transmitting coils and the diameter of the coils themselves [7]. However, the coils themselves cannot be arbitrarily large as many applications require smaller designs for embedded devices. Thus, a compromise must occur. Engineers must choose whether to use a coil at all and instead use a spiral configuration, which has its benefits that warrant consideration [26]. Additionally, regards to the number of turns in the coil, the gauge of the wire, and the shape in which the coil is made must be considered during the development process [31].

Once constructed, there are a plethora of factors in the physics of coil construction that need to be addressed. One fact that plagues these constructs is the losses due to the skin effect on their wires. A solution has been proposed to solve this problem by using a surface spiral layout rendered in Figure 7, which has shown in models that it can minimize this phenomenon's impact [31]. Finally, the coils themselves can be adapted to the system operation even after construction. By building multiple coils and connecting them with electrical relays, the ability to increase and decrease the number of windings provides an opportunity for impedance matching between the transmitter and receiver, improving system efficiency and thus power output [6].

3.3. Frequency Selection and Tuning

One of the most important characteristics of this type of wireless power transmission is the frequency at which the device operates. Higher frequencies can carry more energy over longer distances but at the expense of lower efficiency and higher resistance across the coils [6]. Lower frequencies are easier to operate over and succumb less to phenomena like the skin effect on the antennae but often cannot propagate the same distances as with the higher frequencies [31]. However, most researchers agree that utilizing the 13.56 MHz Industrial, Scientific, Medical band is not only a happy medium between these two choices but it is also pre-approved in most countries for uses outside of simple radio communication as devices such as RFID cards and medical instruments often utilize this wavelength [9].

Once selected, there are scenarios in which tuning the frequency will dramatically improve system efficiency. The negative effects of misalignment, phase change, and distance change can all be mitigated by adaptively changing the frequency of resonance to maximize system performance. Once the power data is gathered via a directional coupler or a vector network analyzer (VNA), the controller circuitry/hardware can make gradual adjustments and adjust the frequency accordingly [29]. However, this approach is not without its problems. Most frequency tuning mechanisms shift the operational wavelength orders of magnitude further than what the approved bandwidth would be [29]. Because countries are strict about how specific frequencies are used, these mechanisms cannot be utilized in the real world as their functionality is inherently illegal [9]. When limited to the specifically approved bandwidth, the tuning effect's impact is minimal and is not worth the engineering time and expense of its implementation. For these reasons, most frequency tuning implementations are reserved for laboratory experimentation only, as there is little chance they will see applications in any industry [6] [26].

3.4. Impedance Match Networks

3.4.1. Types of Networks

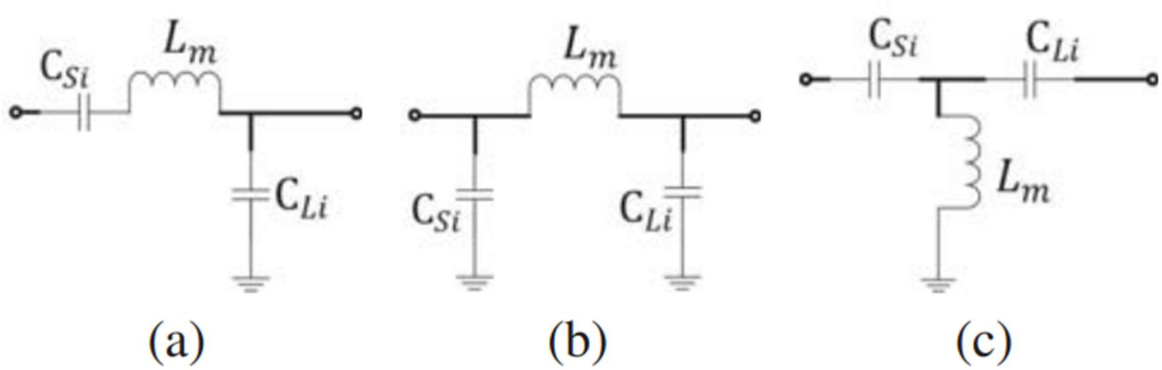

Figure 8: Schematics of IM networks (a) L-match (b) π-match (c) T-match [32]

Impedance matching networks are common tools to enhance performance in systems involving high-speed or radiofrequency signals. Often, the given impedance of a signal generator might differ from the antenna's impedance which can differ from the impedance generated between the antennae and differ between that receiver antenna and its load. Noting this can occur, engineers have since developed schemes that can match impedance along a signal's transmission line to avoid this problem and increase system efficiency. The L-match is the most fundamental of the three shown in Figure 8, and the π-match and T-match circuits are

L-match circuits combined with respect to either the parallel or series element. Each has its specific benefits and drawbacks, whether it be simplicity, ability to equalize impedances, etc. [32].

3.4.2. Optimization of Network Parameters

While the static matching network can perform as expected in a static environment, given that wireless energy transmission offers the benefit of increased mobility to electronic devices, there exists a need for a dynamic matching network. Research has been conducted on such a circuit using a variety of foundational matching networks. These networks have external circuitry connected that can change their component's values and thereby equalize more than just the initial impedance [9] [32] [33]. This system can be driven by an optimizing algorithm run by a microcontroller, a host computer, or a VNA. Most of these controls work iteratively, however, and do not adjust as rapidly as the holistic system changes. However, when they are implemented, they are successful at improving the overall efficiency of the energy transfer.

3.5. Load Matching

3.5.1. DC/DC Converters

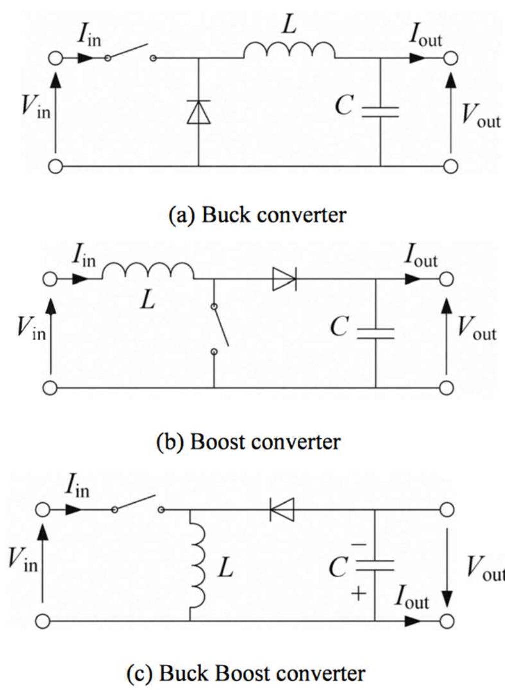

Figure 9: Various DC/DC converters [34]

DC/DC converters change DC levels from one voltage to another, which means they can serve as a variable impedance circuit depending on the duty cycle on which it is controlled. There are three main types of converters which are shown in Figure 9. Buck converters transform the input DC level to a lower output voltage. In other words, they can simulate a load at the same level or greater than the system load going up to infinity, ideal for circuits with low resistive load to increase impedance range. Boost converters change the input DC voltage to a higher one, meaning they can simulate loads up to and including the resistive load of the system; these should be used when the inherent circuit impedance is high. Buck-boost converters can shift the input voltage both higher and lower depending on their configuration and operation making it the most versatile topology of the three [10] [34].

3.5.2. Adaptive Operation

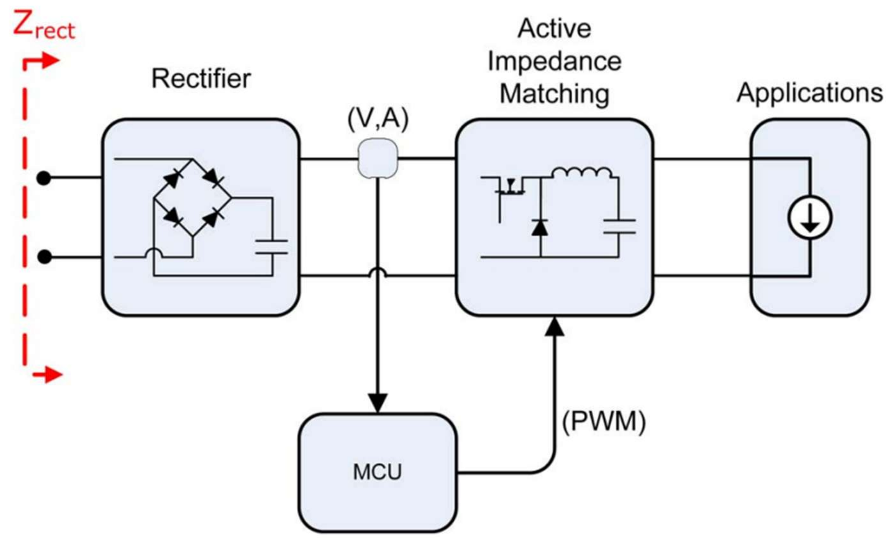

Figure 10: Block diagram of a load matching system maximizing power throughput [9]

Dynamic power matching of the rectified energy at the receiver end has shown impressive improvements in efficiency and consistency in operation. By continually changing the duty cycle of the DC/DC converter, a controller circuit or computer can match the specific load needed for the rest of the system. Multiple parameters can be chosen to measure performance, such as output voltage, amperage, wattage, S parameters, or direct calculation of the load conditions. Figure 10 shows a diagram in which the rectified energy from the resonant coils is led into a buck converter operated by a microcontroller. That microcontroller uses a digital multimeter to change the duty cycle of the conversion with its built-in pulse-width modulation (PWM) output; the output from the converter is then supplied to the load represented as a current source labeled applications. The microcontroller uses a power-point maximizer algorithm to match the load of the converter to the application provided [9].s

4. Research Objective

In this study, a two-coil system is constructed. Each coil generates an oscillating magnetic field that can resonate with the other so that energy transfer can occur at moderate distances. The overall design isolates components and optimizes parameters of their architecture to maximally increase end-to-end efficiency while in operation. The scheme should both prove the effectiveness of the impedance matching for the coils and the adaptive rectification process to match the load connected to the system and show this by improving the power throughput from the transmitter to the receiver.

To highlight this phenomenon, the system utilizes a custom gradient descent algorithm that searches for operating conditions needed to maximize efficiency. However, rather than settling into a steady-state and ending the search, it continually explores the value-space regardless of finding a temporary maximum, which can accommodate circumstances when one or both coils may be in constant motion and their local parameters (and thus the search spaces for the algorithm) are in constant flux. In addition, the system optimizes load balancing at the receiver's end and again utilizes the constant search process.

The goal of these enhancements is to demonstrate that this structure can perform equally well in both static and dynamic environments. Ideally, this research could aid in the development of a real-time charging-at-a-distance mechanism in which devices such as robots, cellular devices, or other mobile electronics are charged regardless of their location, alignment, or movement through space. By not assuming anything about its environment, the architecture should be highly adaptable to whatever circumstances it must face. It is also flexible which is ideal should future upgrades need to be implemented. Determining that this model works establishes a foundation for new research to focus on other promising areas for optimization and subsequently added to this system.

5. System Design and Overview

5.1. Data Aggregation and Controls

All system controls, data collection, and system verification are run using low-power AVR-based microcontrollers. Specifically, every optimization circuit is managed by Adafruit Trinket M0s, which are chosen due to their small size, low cost, and speed. Their high clock rates and general-purpose input/output (GPIO) functionality make them ideal computers to run the search algorithms and update the circuitry without unnecessary delay or bloat. Each of these boards assesses the performance of its subsystem either by measuring its power output directly through its native analog-to-digital converters (ADCs) or through an INA219 digital multimeter chip which they communicate over I2C. This assessment is the metric by which the search algorithm determines the success of its decisions, and it is used to calculate whatever changes (if any) should be made. As each board collects measurements from its subsystem, it sends the voltage, current, power, and time data to a controller Arduino Uno board.

This controller collects the information from all the boards in the system, sorts the incoming data by its timestamp, and sends the data to a host computer in a CSV file format for long-term retention and future analysis of the data. Additionally, this controller Arduino automatically runs any tests specified by the host computer while verifying that each part of the scheme is running to its proper specifications. If any verification failure occurs, the controller Arduino stops the test, alerts the host of the event, waits for the host to fix the error, and then restarts the test entirely. This procedure ensures that no direct human intervention is required once the resonance system activates. After the tests are complete, the data gathered is analyzed using Python libraries, specifically NumPy, Pandas, and Matplotlib. The final end-to-end efficiency, as well as data visualizations, are computed from the host computer.

5.2. Signal Generation and Amplification

The system starts at the transmitter with the signal generator and amplification. The AD9834 from Analog Devices is a signal generator that is selected due to its wide frequency range (up to 75MHz) and compatibility with AVR-based microcontrollers. The chosen frequency is 13.56MHz, selected for its designation internationally as the Industrial, Scientific, Medical band (ISM). This frequency band is perfect for testing as it is cleared for uses other than radio communication, meaning that a future system can use it for wireless power delivery. The controller Arduino sets the output frequency of the signal generator as well as its shape to sinusoidal.

Once generated, the transmission line is initially matched to 50 Ohms and conducted to a two-stage amplification circuit. Using a couple of OPA552 operational amplifiers from Texas Instruments, the input power of 12dBm can reach upwards of 40dBm based on the gain of the amplifiers. The gain is set by using two digital potentiometers whose values are programmed by the controller Arduino. The output is conducted to the next part of the system, but for verification purposes, a 1M Ohm resistor is connected to the transmission line which is connected to a full-wave rectifier. The rectifier's output is connected to an ADC input pin on the controller Arduino. After calculations, it compares the measured power output to the expected power output. If they match, the test is allowed to continue; otherwise, the test ends, and the host is prompted to ensure that all the connections are valid before continuing.

5.3. Coil Construction and the Impedance Matching Circuit

After the signal has been properly created and amplified, it travels to the coils to induce the resonance effect and begin energy transfer. The coils are made of 22-gauge wire configured in a spiral configuration of ten loops. Each loop is about 1 – 2cm apart from its neighbors and has a total diameter of 100 cm. The large design of these coils is to ensure that power can be effectively transmitted throughout the entire target range up to one meter.

However, these coils are more than likely to have mismatched operating impedances because the system is not calibrated to the specific distance (or any distance) between them. Thus, each coil has an impedance match network; a frequent practice in any radio communication, but unlike most, this network can change its values to properly match the overall impedance. The pi-match network is selected because it can match a range of impedances above and below 50 Ohms that other networks, such as L-match or LCC-match, cannot mimic. The pi-match scheme is implemented using a fixed-value, high-power inductor in series and two variable capacitor networks in parallel.

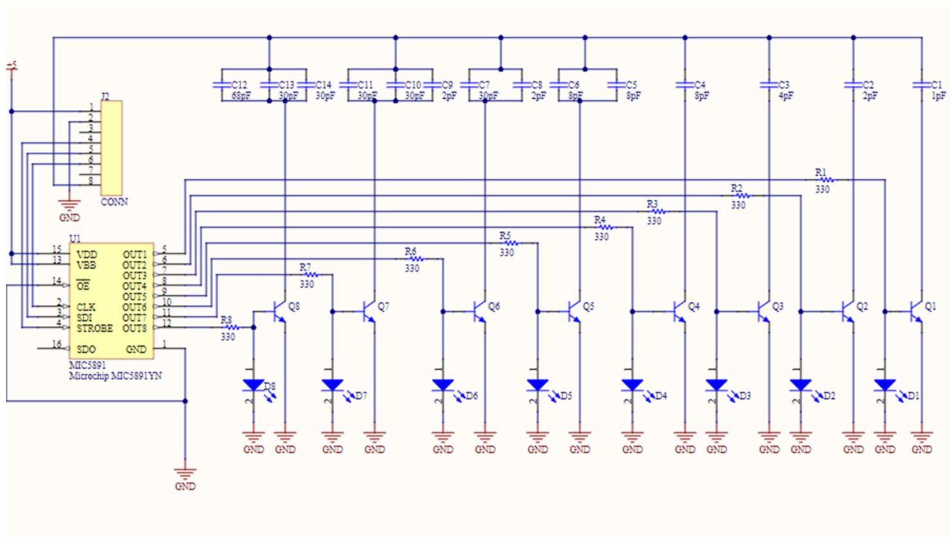

Figure 11: A schematic drawing of the capacitor network circuit

The network, shown in Figure 4 consists of an array of capacitors whose values increase by powers of two from 1pF to 128pF in parallel. Using NPN transistors as switches to which capacitors are connected, the network can create a range of all capacitances from 1pF to 256pF. The transistors are controlled by a Trinket M0 microcontroller through an 8-bit shift register. The shift register accepts one byte of serial data (in our case, the desired capacitance) and outputs every bit as an output to its corresponding switch, meaning the Trinket can control all eight transistors with three pins, ideal given its small number of GPIOs. These capacitor values are the variable in which the search algorithm, shown in Figure 12, changes to optimally match the impedance and thus achieve the maximum power output.

5.4. Gradient Descent Search Algorithm

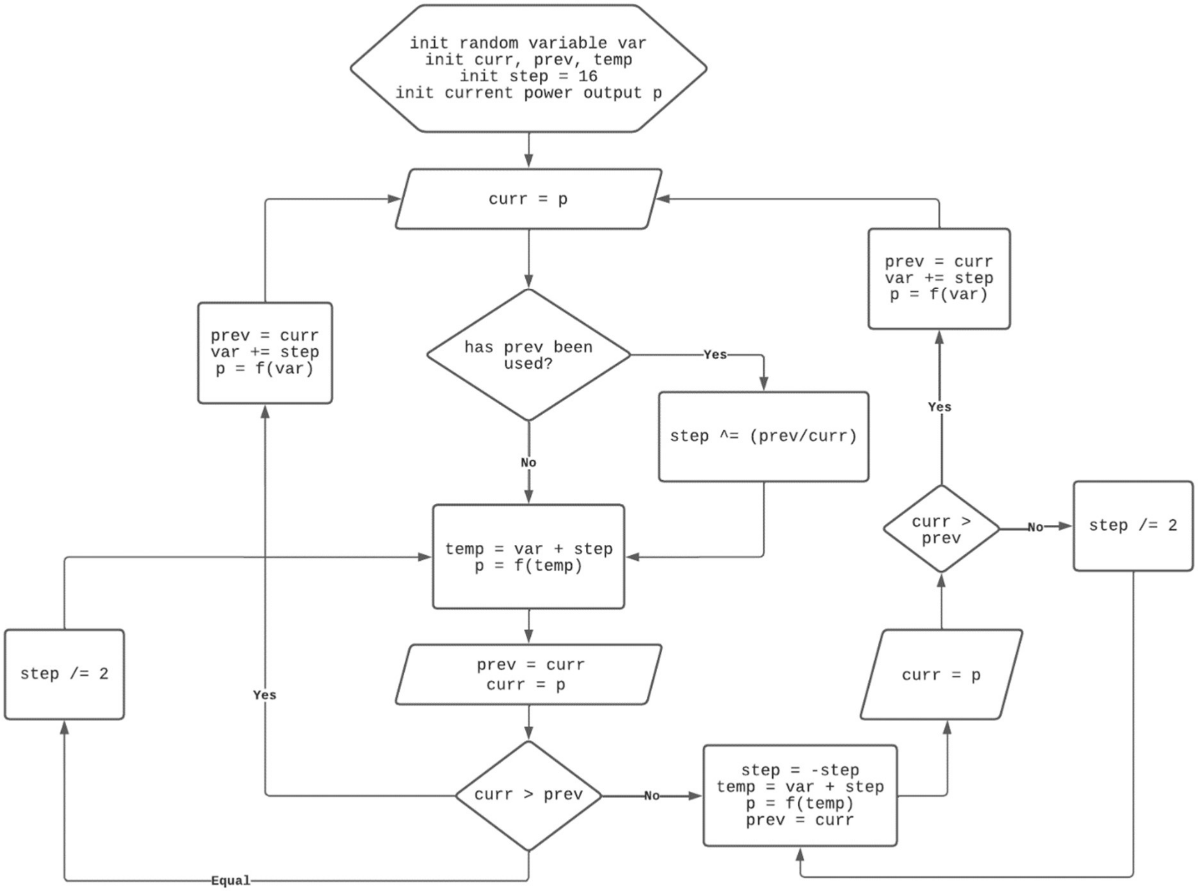

Figure 12: The optimization algorithm outline used for both impedance and load matching

The algorithm proceeds as follows:

1. *The optimization variable "var" is set to a random value. Buffer variables representing the current and previous power levels are initiated as "curr" and "prev" respectively, a temporary variable "temp" is initiated, and a "step" size for the shift amount of the random variable is set (arbitrarily) at 16.*
2. *A power level reading is taken and assigned to the variable curr.*
3. *A conditional statement then is presented: has the variable prev been used?*
    a. *If so, set the step variable to itself raised to the power of the ratio of prev divided by curr*

    b. *If not, just set the temp variable to be the sum of var and step, and temporarily apply the value of temp to the system.*
4. *Set the variable prev to the value inside curr, then take another power level reading and set the new value to curr.*
5. *A conditional statement is presented: is the value of the variable curr greater than the value of the variable prev?*
    a. *If so, set the value of prev to the value of curr. Set the value of var to the sum of the value of step and the value of var. Permanently implement that change into the system. Then proceed to step 2.*
    b. *If curr and prev are equivalent, set the value of step to half of its current value. Then proceed to step 4.*
    c. *If not, flip the sign of the value inside step, re-add the value of temp and step and assign that value to the temp variable, temporarily set the value of the system to the new temp variable, and assign the value of curr to the prev variable.*
    d. *Take a new power reading and assign that value to the variable curr.*
        i. *Another conditional statement is presented: is the value of curr greater than the value of prev?*
            1. *If so, set the value of prev to the value of curr. Assign the value of the sum of var and step to var. Permanently apply the value var to the system. Then proceed to step 2.*
            2. *If not, set the value of step to half of its current value. Then proceed to step 5.c.*

5.5. Adaptive Rectification and Load Matching

Finally, after propagation and another impedance matching network for the receiver coil, the signal reaches the adaptive rectification and load matching stage. The AC signal is converted to DC using a full-wave diode rectifier, but instead of being directly converted to an arbitrary voltage and current, this system utilizes the buck-boost DC-DC converter to actively equal the load of the rectified power draw to the load on the system. This technique of using a DC-DC converter to match overall impedance has been proven to be effective in improving the end-to-end efficiency of wireless power transfer systems as it recovers energy that would otherwise be lost if this process is static.

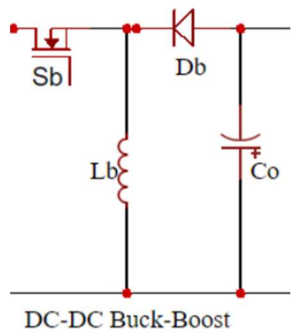

Figure 13: A schematic diagram of a DC-DC Buck-Boost converter [10]

However, the buck-boost converter shown in Figure 13 improves on this technique by offering a theoretically infinite range of positive impedances simply based on the duty cycle of the conversion. If the duty cycle could be actively tuned, any potential load can be matched. Thus, the converter is controlled by another AVR microcontroller which regulates the rate of rectification using the same algorithm as the impedance matching algorithm with the control variable being the duty cycle of the power MOSFET. That AVR controller also controls a digital potentiometer that represents the entire load on the system.

6. Testing Procedure

To measure the effectiveness of the optimization features and the independent nature of the system, we must establish a baseline functionality by turning off all the improvements to the design. Once established, we then evaluate each feature individually before finally bringing them both online at the same time, which should allow for a diverse range of datasets to look at as well as provide an honest perspective on the effectiveness of the proposed design. The steps for each test shall be as follows:

1. Place the transmitter coil on a specific spot on a flat surface
2. Place the receiver coil directly in front of the coil
3. The controller Arduino will note the performance of 1W, 5W, and 10W at the location and display it on the host computer
4. Once displayed, move the receiver coil back 50 cm
5. Wait 5 seconds to allow the system to stabilize and gather measurements again
6. Repeat steps 3 – 5 until the receiver coil is one meter away from the transmitter

NOTE: When impedance matching is not enabled, the capacitance values of all the networks will be set to 200pF.

7. Experimental Results and Analysis

7.1. Results of Control Experiment

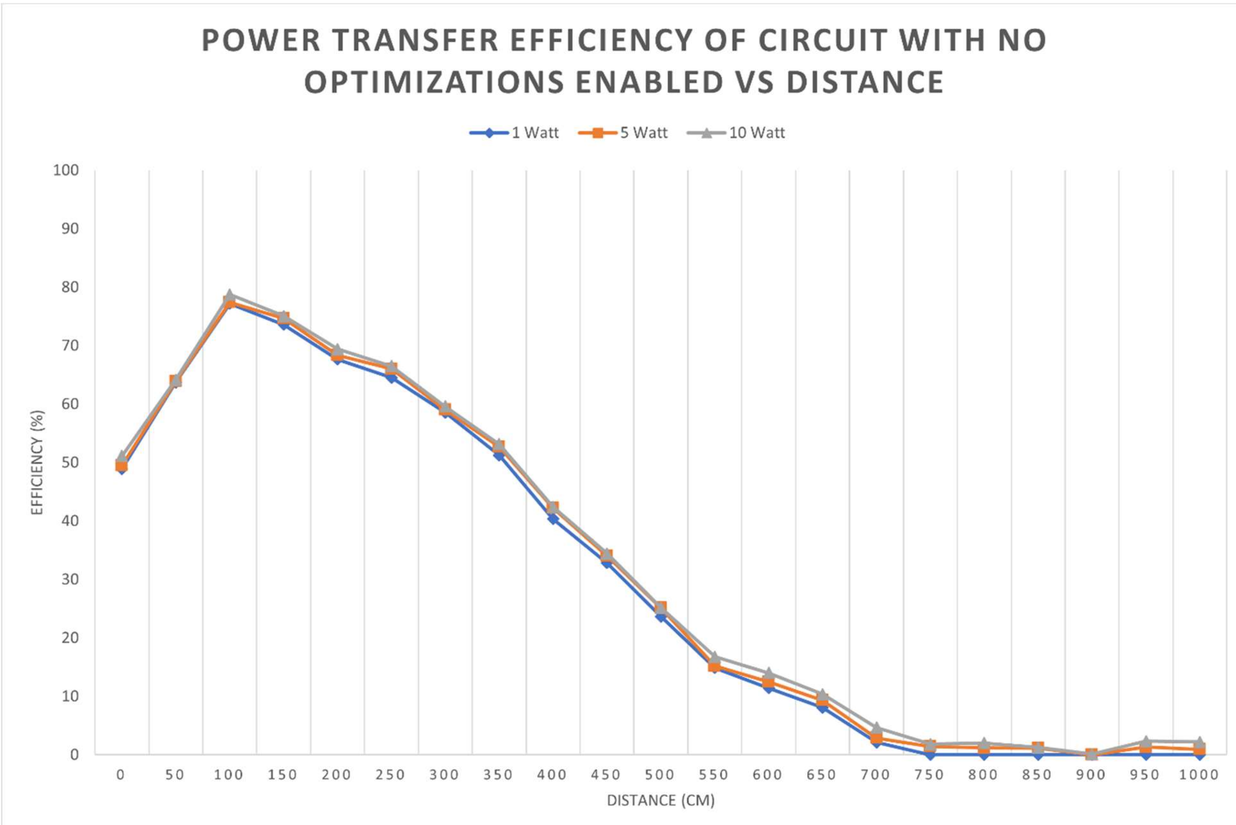

Figure 14: A graph of the system's efficiency with no optimizations enabled

Figure 14 shows the data from the control experimentation, in which no optimizations are activated during the testing process and every capacitor network is set to operate at 200pF. From experience with previous research, the peak at 79.7% and an average of 30.3% in operating efficiency when the ratio of the distance between the coils (D) to the coil diameter (d) equals one is expected as the capacitor values are set to ensure this behavior occurred, establishing a baseline that the experiment does work as intended. Notably, the performance when the distances are smaller than d/D = 1 is lower than initially anticipated based on other research but could indicate that a part of the system is not performing to its design during this use case. Once d/D > 5 however, the performance drops significantly, and past d/D > 7, the power seen at the load is almost negligible. This fact and the uneven shape of the overall curve demonstrate the need for optimization techniques in general, as there is room for improvement while the apparatus is in operation that needs to be explored. One thing to remark is that the performance of the system enhanced as the power of the systems increased. This behavior, while unexpected, could be explained by the fact that the operational amplifiers used to perform better in high-gain situations, and could explain the trend of increasing efficiency as power throughput also increases.

7.2. Results with Impedance Matching Feature Enabled

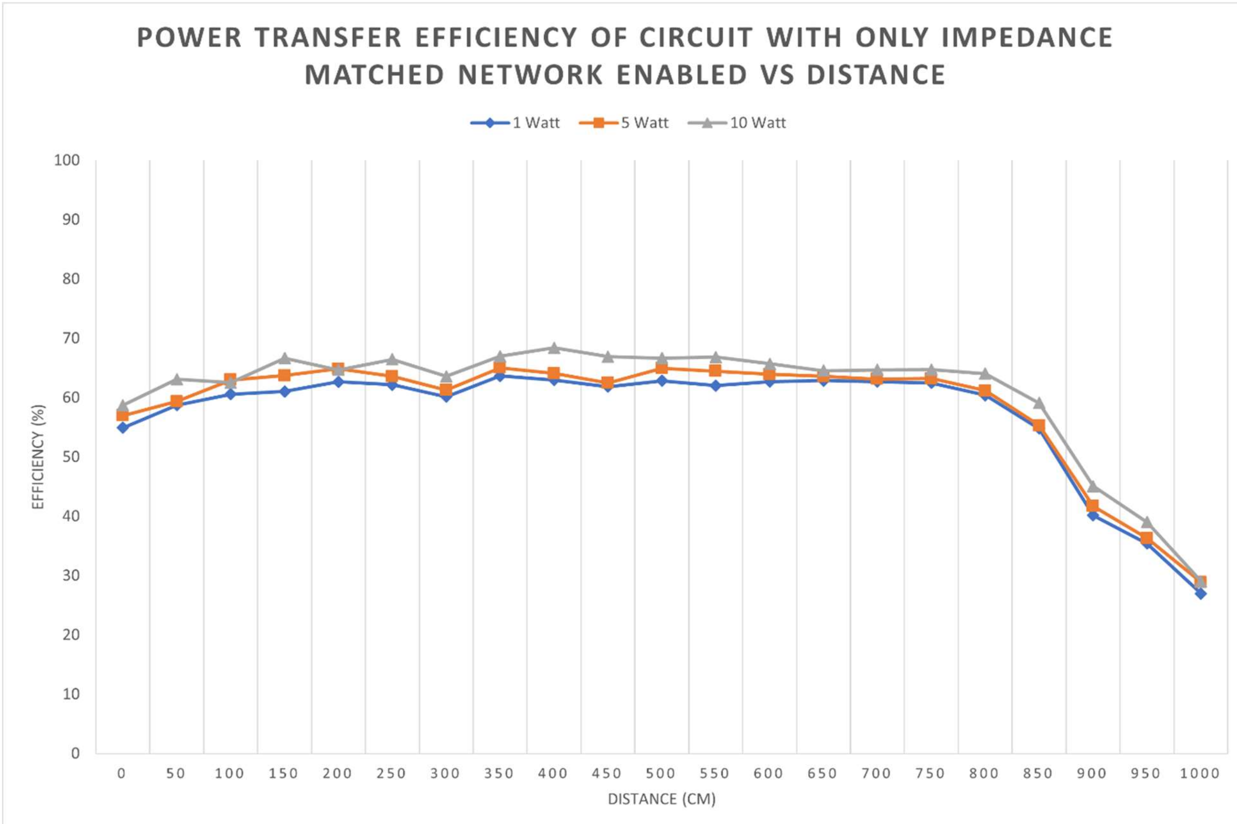

Figure 15: A graph of the system's efficiency with only impedance matching enabled

Figure 15 displays the performance of the wireless power transfer system when only using the impedance tuning algorithm for the coils. As stated previously, the algorithm is designed to ensure that the coils are optimally matched to each other regardless of initial configuration, which in turn improves the effectiveness of the magnetic resonance transfer field. Like the previous experiment, we see that the system performs better when working with higher power levels and that after a certain high gap distance (d / D > 8), the power efficiency drops dramatically. What is different is the fact that the overall *average* efficiency has almost doubled with the system operating at an average of 59.8% across all power levels. What is also remarkable is that the peak efficiency of the system has dropped to a maximum of 65.3%. This might be due to the algorithm not finding the global maximum in the time provided. The decrease could also arise from the fact that the algorithm could inadvertently work to smooth the efficiency curve, leading to more consistency in performance.

7.3. Results with Load Matching Feature Enabled

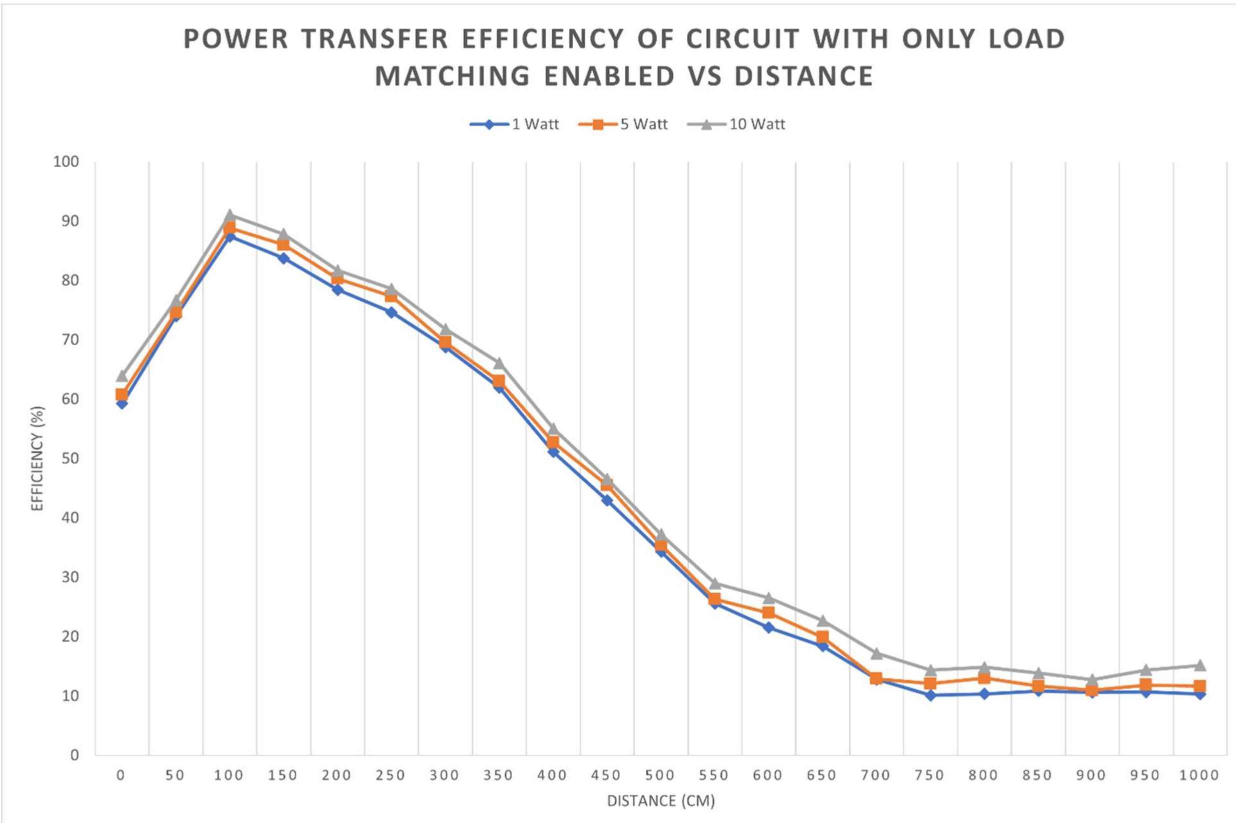

Figure 16: A graph of the system's efficiency with only load matching enabled

Figure 16 highlights the performance curve of the wireless power system when only the load matching feature is enabled, and the capacitor values from the network are hard coded to 200pF. With the average efficiency at 41.5% and the peak efficiency at 91.1%, the load matching provides a 14.3% peak efficiency boost, and the average efficiency increases by 37.0%. The improvement shows that the load matching algorithm has a non-negligible effect on performance by reclaiming the energy that may be lost during the rectification process. This optimization does not change the performance in the same manner as the impedance matching for the coils, however, as it still resembles the control experiment's efficiency curve. Load matching does not influence the trend of higher power output leading to higher end-to-end efficiency, further making a case that the op-amps are the cause of this phenomenon and not from the rectification process. The drop-off in efficiency does occur slightly later at d/D >= 5.5, which shows that there remains room for improvement.

7.4. Results with Both Load and Impedance Matching Features Enabled

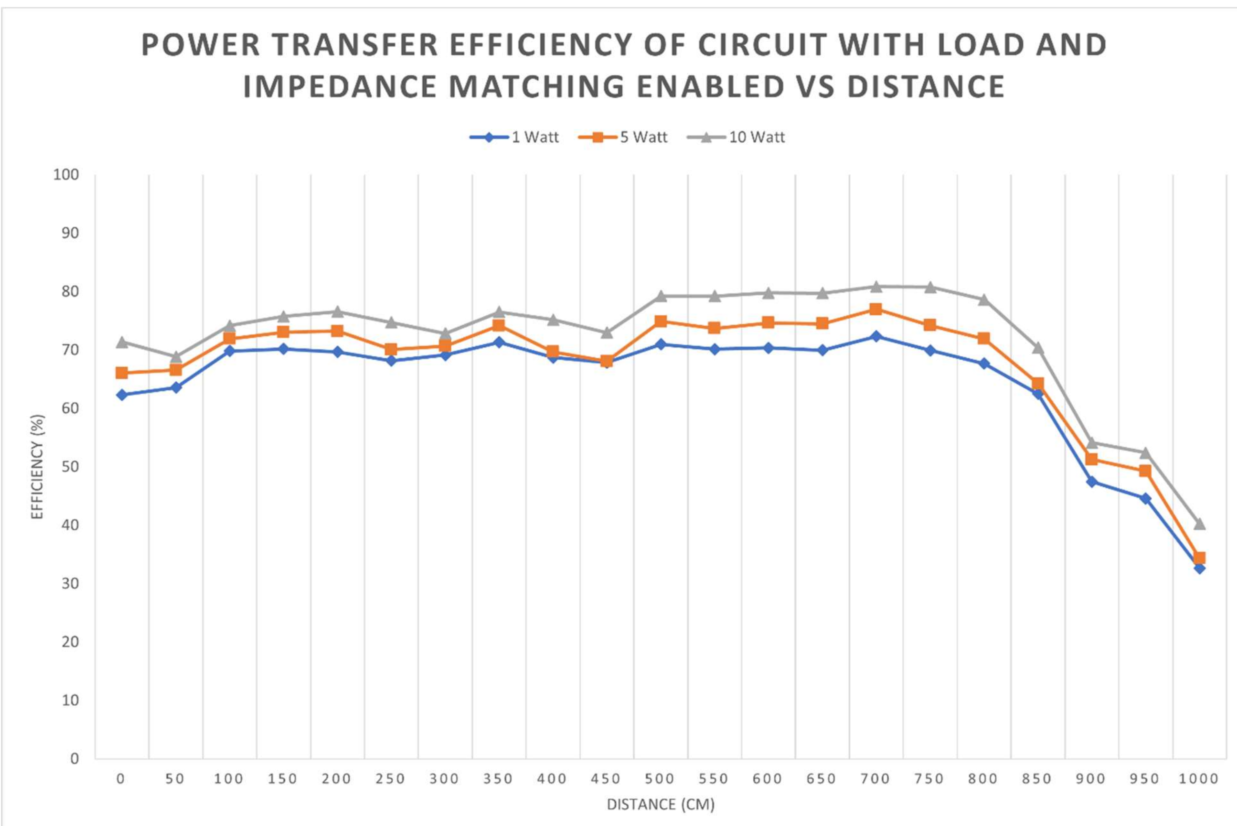

Figure 17: A graph of the system's efficiency with both optimizations enabled

Figure 17 shows the performance of the combined effect of both the impedance matching algorithm for the coils and the load matching algorithm for system output. It performs as expected given the data of the previous experiments: a flattening of the curve over the control experiment and an overall higher power throughput. Peak efficiency is at 80.8% and average efficiency is at 68.7%, but the fact that the peak efficiency occurred at 750 cm is noteworthy as that typically denotes where performance begins to suffer in the other experiments. The effect of the power input on the higher efficiency trend seems to work significantly more here than in any of the previous trials. The improvement in average efficiency over the control means that the effects of both the optimizations not only work as intended but that they complement each other and have a cooperative effect.

8. Future Considerations

Each of the tests ran consistently and according to its predefined specifications. As shown in the previous section, the results are satisfactory and provide hope for the future development of the project. However, several challenges require discussion, as well as potential improvements that may rapidly grow the scope and maturity of the project.

8.1. Improvements to Project Construction

The construction process outlined in this study, while successful in demonstrating the effectiveness of the proposal for the project, has room for improvement. More consideration should have been given to the potential electrical noise both during the design process and assembly, as using breadboards and hand-soldered components only give more opportunity for erratic behaviors to arise. Using printed circuit boards that utilize impedance-matched traces and isolated ground levels for signal and power circuits can also assist in mitigating unwanted effects. Using RF-specific components such as less fault-tolerant, highly accurate resistors, and capacitors will offer more consistency in the performance and accuracy of the experiment, which is important for replicability. In addition, ensuring that the area in which the study is conducted does not have a lot of intermittent EM radiation would be ideal, as there is likely some non-negligent level of interference when tests are conducted.

8.2. Modifications to the System Design

Another aspect that could be improved in this research is the design of the system itself; certain adjustments or additions to the layout have the potential to further increase efficiency even more. There are available opportunities to enhance the coil technology, as this analysis ignored them outside of its initial design. Changes to their shape, the amount of them in the system (four coils as opposed to two), and whether it should be built as a spiral or coil are several options that can be explored [31]. Finally, there should be a focus on strengthening the resonating magnetic field, which can occur by using multiple transmitters simultaneously or metamaterials that can focus the magnetic flux in a particular direction [35] [6] [36].

8.3. Quality of Testing Methodology

Lastly, the testing methodology can be made better. Given that this system is supposed to model real-world performance, situations such as pairing to multiple receivers or receivers of varied sizes (or both) should be assessed. Interference should be considered in the experiments as well by employing both physical obstacles and electromagnetic radiation as its sources. More data is needed to fully understand the effect of the system load-matching algorithm; this data can come from specific tests isolating the performance of multiple power levels at one distance, as there might be an optimal power output that cannot be determined with the current data. The tests should be more precise and thorough which can be done by gathering data on more distances and power levels; the trials should also consider phase and misalignment to paint a more realistic picture of its usage.

9. Summary

In this paper, a wireless power system is proposed using magnetically resonant coils as a solution to high-efficiency energy transfer in situations where a wired connection is not ideal or possible. This system automatically changes its circuit topology by using multiple AVR-based microcontrollers running gradient-descent algorithms that maximize efficiency and power output. Targeting two components in the design, the pi-match impedance network on the transmission line to the coils and the receiver-end rectifier that provides DC power to the system's load, the on-board computers can alter them to maximize throughput when the gap between the coils changes during operation. Each dimension of optimization is isolated to evaluate its efficacy first, and then their combined effect is studied. When the impedance match and system load match algorithms are activated together, the average efficiency increases by 126% over the tested distances, and the peak efficiency rises by 1.8% over the control. By showing the system performs more consistently as the distance between the coils increases due to its self-correcting nature, this study has demonstrated that this system can power devices that may be moving during the charging process.

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