A Review of Modelling Techniques Used in the Analysis of Wireless Power Transfer Systems

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Zusammenfassung

Wireless power transfer is currently emerging as an important technology across a wide range of industries. The great variety possible in wireless power transfer systems presents issues in performing general analysis. This review presents details of current modelling techniques used in the analysis of wireless power transfer systems, with specific emphasis on the approximations that restrict their applicability to given systems. The intention of the review is to aid the understanding of basic wireless power transfer mechanisms and associated modelling techniques, in order that a general modelling technique may be developed.

1 Introduction

Consumer demand for high-performance electronic devices such as smartphones, tablet computers, laptops, etc. is ever increasing. Not only that, but in order for the manufacturers of these devices to gain the edge in the market they must continually stay one step ahead of their competitors by incorporating state-of-the-art technologies into their products. This produces generations of devices that are smaller, lighter and more powerful than their predecessors. The increased functionality of a device places more demanding requirements upon its power source. For mobile devices the source is a battery, which typically will have a lifespan of a matter of hours when feeding a device that is operating at full functionality. For more static devices, power cables can often get tangled and restrict the location of a device. Indeed, the supply of power to everyday electronics can often be problematic.

There are however a number of promising solutions to the problems associated with the supply of electric power. Wireless Power Transfer (WPT) can be defined as any process that transmits electrical power to one or more objects via non-electrically conductive paths. The complex nature of electromagnetic behaviour means that there are many ways in which WPT can be achieved. The choice of which method of WPT to use is entirely dependent upon the requirements of the system (such as transmission distance, output power, etc.) in question. Such a broad range of possible transfer mechanisms introduces issues in the mathematical modelling of the system. In order to formulate a solution, approximations are made which place bounds on the allowable values of key parameters such as frequency and transmitter/receiver size. This can lead to inefficient system design and/or limit their potential.

Current reviews on WPT exist in terms of its history [1][2], current developments [3][4][5], mid-range operating principles [6] and the equivalence of mid-range modelling techniques [7]. A complete review on the history, applications, physics and modelling of WPT as a whole has not, to the authors' knowledge, been presented.

The intention of this paper is to first introduce WPT briefly in terms of its history and modern day application. Secondly, the ways and means by which WPT can be achieved are described via basic electromagnetic theory. The paper will then proceed to review the main modelling techniques used to characterise WPT systems. Finally, the paper then introduces the research effort at The University of Reading to develop a model that generalises the description of WPT, such that it is applicable to the broad range of WPT systems that currently exist.

2 A Brief History of WPT

The origins of WPT can be traced back to the works of two of the most prominent figures in electromagnetic theory; Heinrich Hertz and Nikola Tesla [1][2]. Hertz's work in practically demonstrating electromagnetic wave propagation (previously theoretically proposed by Maxwell) allowed him to transmit, and subsequently receive, high-frequency, focussed beams of radio waves. Some 10 years, Nikola Tesla later began his experiments into WPT at his Colorado Springs facility [8]. Tesla's work was particularly involved with incorporating resonance into his systems. With this, Tesla hoped to provide free energy worldwide by creating a global resonant WPT system. Tesla didn't achieve his goal as his financial resources were depleted before he could complete his first transmitter at Long Island. The termination of Tesla's project spelled the end of research into WPT for some time.

The next major milestone in WPT was marked by the creation of devices that could produce high-powered microwaves, such as cavity magnetrons and velocity modulated beam tubes. In 1964, Raytheon Company developed a helicopter capable of sustained flight, powered solely by microwaves. The helicopter weighed 2.3kg and was successfully flown for 10 hours, achieving a maximum altitude of 50 feet ($\approx$ 15 metres) [1][2]. The end-to-end (d.c. to d.c.) efficiency of the system is not specified but given the infancy of the rectenna[1] technology it is speculated to be low ($\approx$ 10%).

The next 10 years of research in WPT was focussed on developing highly efficient rectennas in order to improve the overall efficiency of microwave transmission systems. In 1974, a NASA-sponsored experiment at JPL's Goldstone facility successfully implemented a long distance (1.54km), high-powered (30kW) microwave WPT system through the use of a highly efficient rectenna array (84%) [1]. The purpose of this experiment was to determine the feasibility of the Solar Power Satellite (SPS) concept that NASA was developing at the time. The SPS is designed to beam down the sun's energy from its platform in orbit to a large rectenna on the surface of the Earth in order to provide a clean, sustainable energy source. Despite the successes of the experiment at JPL Goldstone and the continuing improvements being made in the field of microwave transmission, the project was pursued no further. Rectenna development continued with the introduction of higher frequency (up to 35GHz) microwave generators, but no other significant advances in WPT were made regarding microwave transmission.

In 2007, WPT regained the scientific spotlight once again after Soljačić et al. at MIT demonstrated a high efficiency, mid-range WPT system based upon strongly coupled magnetic resonance [9][10]. By utilising the self resonance of an open-circuited helical coil, the team were able to transfer 60 Watts over a distance of 2 metres at 40-50% efficiency. The inclusion of resonance in the team's system bears striking resemblances to the works of Tesla over a century beforehand. The use of resonance was a key

[1]The term "*rectenna*" stands for "*rectifying antenna*" and is used to describe the conversion of microwave or radio waves into d.c. electric power.

development in the field of WPT; ordinary magnetic induction alone, such as is employed in transformers, is far more sensitive to coil misalignment and separation distance, leading to efficiencies too low to be practical for WPT systems over appreciable transmission distances.

The MIT team's success lead to a resurgence in interest in WPT and two noteworthy advances regard frequency tuning [11] and impedance matching [12]. Frequency tuning techniques aim to select the optimal transmission frequency (optimal in the sense of leading to the highest efficiency) based on the positioning of the receiver coil. Impedance matching techniques minimise the mismatch between the receiver impedance and the impedance of the output circuit, ensuring the maximum amount of power reaches its end target. With the use of feedback, systems can be designed that can adaptively achieve frequency tuning and impedance matching in order to achieve greater spatial freedom. Despite recent advances made in improving the range of WPT systems, the goal of creating wirelessly-powered environments of appreciable size is not presently realizable.

Over its history, WPT technology has evolved greatly. There is still much room for improvement, particularly in terms of increasing the transmission distance and guaranteeing system safety. There are however a large number of applications where current WPT technology has been succesfully implemented or is suitable for implementation within existing electronic devices and these are presented in the next section.

3 WPT Technology & Applications

3.1 RFID

Perhaps the most common example of the incorporation of WPT was in the use of Radio Frequency Identification Devices (RFID). These small tags are used for a variety of identification and tracking purposes, and can be powered wirelessly via radio waves or by electromagnetic induction. These methods can act as the sole power source (known as "*passive*" devices) or used in conjunction with a battery incorporated with in the device ("*semi-passive*"). Devices that powered solely by a battery are known as "*active*" devices and can achieve much longer transmission distances that passive devices (several metres vs. tens of metres). Improvements to passive devices have been proposed by utilising energy harvesting techniques within the device. Harvesting techniques work by capturing energy from background electromagnetic radiation, converting it into electrical power and then storing it. Although the power associated with background radiation is very low, the low-requirements of RFID tags and certain sensors mean that the incorporation of energy harvesting techniques provide a feasible WPT solution.

3.2 Biomedical Implants

Biomedical implants are extremely important devices in the health industry. These devices have widespread use throughout the body and treat a number of conditions. Examples of such devices are pacemakers, prostheses and cochlear implants. The largest component of these devices is usually the battery. Not only that, repeated surgery to replace the depleted batteries places the patient at risk. As such, it is hoped that WPT can be implemented to recharge the battery or replace it altogether. Furthermore, reduction in size of the implant leads to greater comfort for the patient. Due to the proximity of sensitive tissues however, any implantable device will have to satisfy strict safety requirements.

Misalignment between transmitter and receiver can cause both excessive heating in the device and surrounding tissue. Additionally, power levels and frequency must be limited according to the relevant exposure guidelines [13]. Satisfying such strict criteria will undoubtedly lead to compromises in system performance. Current safety-led research has shown that efficient, safe WPT for biomedical implants is possible in the low-GHz (1, 1.7 GHz) [14] and Hz ranges (180 Hz) [15].

3.3 Consumer Electronics

Another major application WPT has contributed to is in the powering of consumer electronics devices such as mobile phones, tablet computers and laptops. Compared to RFID tags these devices have much larger power requirements and so the incorporation of WPT technology has been restricted to short range, contactless WPT products designed to recharge the battery of the device in question. These products, in the form of charging mats & sleeves, have currently been implemented for mobile phones, but the technology can be easily extended to include charging for laptops, tablets and other similar devices. Indeed, companies such as Microsoft, Apple, Samsung and intel are all seeking further developments of this technology and it is reasonable to expect an increase in the number of products with WPT capability. Having successfully pilot tested their wireless charging tables (which utilise Duracell's powermat technology) in a select number of their USA outlets, Starbucks plans to extend this facility throughout more of their stores. There is however something of a war of standards going on within the consumer electronics side of WPT. the Alliance for Wireless Power (A4WP), The Wireless Power Consortium (WPC) and Power Matters Alliance (PMA) all have their own patented WPT technologies and each are backed by large companies. What this means for the consumer is that there will most likely be compatibility issues between certain products, depending on which organisation the manufacturer's of the products belong to.

3.4 Electric Vehicles

WPT is also set to make vast improvements in the automotive industry. With the increasing number of electric and hybrid-electric vehicles on the road, there is keen interest in developing novel wireless charging technologies for this new-age mode of transportation. A widespead implementation of wireless charging technology for electric vehicles can be found in Milton Keynes, UK. Utilising inductive charging, a fleet of eight public-service electric buses are powered wirelessly. The charging takes place as passengers embark or disembark at specially designed bus stops. Similar systems can be found in Italy, Netherlands and Germany. As an alternative, rather than having specific charging stations, wirelessly powered roads can provide the vehicle with a continuous power supply, increasing the travel distance of a given journey. An example of this can be found in Gumi, South Korea where two buses enjoy this wireless charging facility on a 12km stretch of road. It is entirely reasonable to expect a rapid increase of wireless charging technology on public roads, and as a consequence, more and more electric vehicles to come with wireless charging capability as standard. Furthermore, combining this technology with the recent proposal of solar powered roads, the future of WPT in this area is particularly exciting.

3.5 Space based Concepts

The most ambitious ideas of WPT are related to space based applications. The Solar Power Satellite (SPS) concept, introduced in Section 2, is currently under serious consideration by The Japanese Space Agency, JAXA, who hopes to have a full-scale SPS system in place by 2040. NASA is also revisiting the idea under its 2001 Space Solar Power Exploratory Research and Technology Program (SERT) [16]. The relative infancy and large scale of the project means that there are still many issues relating to system design, beaming duration, location, times and safety [17] that must still be addressed. There a number of factors addressing all these issues, such as atmospheric attenuation, efficient rectenna operation criteria and interference with existing communications, spacecraft and aircraft that restrict the operating frequency and power-levels of the SPS. Initial studies into the concept have proposed end-to-end efficiencies of potentially 45% [18]. Considering the distance of power transmission involved (36,000 km), such efficiency certainly demonstrates initial feasibility of the concept. Other space based concepts such as space elevators and wireless propulsion [19] can certainly be born out of the development of SPS WPT technology, since they share similar implementation issues. Space elevation involves the use of climbers that transport items from the ground to a space platform via a tethered cable. Wireless propulsion uses photon reflection to propel spacecraft through space, leading to vast reductions in the weight of the craft since large fuel storing capacity is not required.

4 Theory: How is WPT achieved?

This section describes the physical mechanisms via which WPT can be achieved. The basic theory behind each method is briefly discussed, with each separated into one of two categories: near-field or far-field.

4.1 Near-Field

Near-field WPT denotes systems that involve separation distances that are within one wavelength, λ ($\lambda = c/f$, where c is the speed of light in vacuum and f is source frequency), of the source. These systems use non-propagating (stationary) electromagnetic fields in order to achieved WPT.

4.1.1 Magnetic Induction & Resonance

Magnetic induction is an electromagnetic phenomenon first described by both Michael Faraday and Joseph Henry circa 1831. It has found widespread use throughout a variety of electronic devices. The most common example of practical implementation of magnetic induction can be found in transformers, which are used to either increase or decrease the voltage in part of an electronic circuit. This transformer effect is essentially the basis of WPT via magnetic induction.

Magnetic induction is the phenomenon by which a time-varying magnetic field through a surface enclosed by a conductor, such as a loop of wire, gives rise to a time-varying current in the conductor. By converting the free-space magnetic energy into electrical energy, WPT can be achieved.

WPT systems based solely upon magnetic induction are able to achieve high efficiency but only over very short air-gaps ($approx$ 95% at 70mm,[20]). Efficiency drops drastically with separation distance (as $1/r^3$, where r is separation distance), and as such WPT systems using magnetic induction are usually denoted as “contactless” rather than wireless. In order to increase the limited spatial extent of efficient

WPT via magnetic induction, resonance can be incorporated into the system [9][10]. System resonance is achieved by tuning the frequency of the transmitting circuit in order to create a field distribution in the space between the transmitter and receiver that maximises the transfer efficiency. The amount of tuning required, quantified by the difference between the optimal frequency and the self-resonant frequency of the transmitter in isolation, is proportional the strength of coupling between the fields transmitter and receiver. The strength of the coupling between the fields is proportional to the spatial "overlap" of the two sets of electromagnetic fields of the transmitter and receiver. Strong coupling is one of the conditions for high-efficiency transfer and is solely dependent upon the geometry[2] of the system.

WPT via resonant magnetic induction has many advantages over other methods. Since magnetic fields do not interact strongly with objects that are "off-resonance", they are safe to use in the vicinity of humans and other electronic devices. Additionally, no line of sight between transmitter and receiver is required since off-resonance objects do not adversely effect the power transfer. These factors, along with the high-efficiency mid-range WPT typically possible, resonant magnetic induction is the most widely applied and researched WPT mechanism.

4.2 Capacitive Coupling

Much in the same way as two magnetic fields can couple together to produce power transfer, so too can electric fields. WPT in this fashion is known as capacitive coupling, since the mechanism by which power is transferred is through the capacitance that builds up between the transmitter and receiver. The charge associated with the transmitter generates an electric field causes a charge build up of opposite sign on a conducting structure placed in the field's vicinity. Much like magnetic induction, the efficiency of power transfer associated with capacitive coupling decays exponentially with transfer distance. The resonance effect once again can be employed to vastly improve the transfer efficiency and distance. Research indicates that WPT systems based on capacitive coupling perform similarly to their magnetic counterparts, and they may even be less sensitive to misalignment between transmitter and receiver. The major drawback with capacitive WPT systems is that electric fields do not share the safety characteristics of magnetic fields, since their relative field strength is much greater, posing a hazard to both humans and electronic devices. For applications that concentrate practically all of the field between transmitter and receiver, such as in charging pads and mats for example, the dangers can be mitigated.

4.3 Far-Field

In contrast to near-field WPT, far-field WPT is achieved via propagating electromagnetic fields and is used to transfer power over distances greater than one wavelength. The absence of a strong coupling mechanism at these distances means that far-field WPT typically exhibits much lower efficiencies than near-field methods.

4.3.1 Electromagnetic Radiation

The coupling mechanism responsible for WPT via electric or magnetic fields breaks down for separation distances that exceed one-half of the source wavelength. In order to achieve WPT past these distances

[2]The term geometry refers to the size/shape of the transmitter and receiver and their separation/orientation relative to one another.

alternative WPT techniques must be employed.

All time-varying electromagnetic sources produce electromagnetic radiation. This is due to the fact that a changing electric field produces a changing magnetic field and vica versa, giving rise to the generation of self-propagating electric and magnetic waves - known as electromagnetic radiation. These waves carry energy away from the source, and the power of the wave typically decays as the inverse square of the separation distance ($1/r^2$, r is separation distance). Drawbacks involving the use of radiative WPT are the requirements of line of sight and beam focussing. Electromagnetic radiation can also produce adverse health and interference effects, placing constraints upon power and frequency. For WPT beyond several metres however, electromagnetic radiation is the only possibility.

Beyond microwaves, WPT is possible at optical frequencies via laser beam. The comparatively lower generation and rectification efficiencies of laser beams [19][18] means that WPT using microwaves generally exhibit higher end-to-end efficiencies. The greater focus and smaller size of laser systems provide the main advantages over microwave-based systems, but until laser beams can be created and re-converted back into electricity at higher efficiencies, microwave WPT systems will dominate.

5 Modelling Techniques Used in WPT Analysis

This section presents the common modelling techniques used in the analysis of near-field and far-field WPT systems.

5.1 Near-field

Near-field techniques refer to modelling techniques employed in the analysis of near-field WPT systems. Specifically, these techniques are used to model resonant magnetic induction and capacitive coupling. The approximation common to all near-field modelling techniques is that the size of the objects comprising the system are all electrically small. This is usually a reasonable approximation for objects with characteristic dimension (such as diameter for a loop) that are less than one-tenth of the source wavelength. This permits the assumption of constant current distribution throughout the system and negates any complex radiative behaviour associated with the system, simplifying the analysis.

5.1.1 Coupled Mode Theory (CMT)

Coupled Mode Theory was first used in the analysis of WPT by the researchers at MIT. Originally developed in the early 1950's and commonly applied in the analysis of microwave devices, CMT provides a general framework that can be applied to a variety of scenarios involving the coupling of electromagnetic resonators [21, Ch 7, pp.197-230].

The term "*mode*" refers to the pattern associated with an electromagnetic field. When two or more modes overlap in space or time, they are able to couple to one another and exchange energy. This produces a coupled mode, a specific field pattern due to the interaction between the individual fields. CMT provides a mathematical description of the extent of this coupling by assuming that the uncoupled mode can be described by a linear superposition of the individual coupled modes [22]. In other words, CMT approximates the coupled mode as a first order perturbation of the uncoupled modes. In the context of WPT systems, this implies that any losses must small compared with the total energy in the system. It is interesting to note that the CMT equations are equivalent to Maxwell's equations, if a complete set is assumed for the mode expansion [23]. Practical use of CMT however typically employs a two-mode expansion only for simplicity.

The use of CMT in the analysis of WPT provides deep insight into the resonance mechanism that is responsible for high efficiency WPT. It can be shown that the coupling actually splits the resonance of WPT into an even and an odd (coupled) mode. These modes lie above and below the resonant frequency of the natural system respectively, and the amount of deviation from this natural frequency is proportional to the strength of the coupling. Both of these modes produce higher efficiencies than operating the system at its natural resonant frequency (typically the odd mode leads to greater efficiency than the even mode as its operates at a lower frequency, reducing both radiative and resistive losses). The fundamental link between the coupling and frequency as identified by CMT provides a method to compute the optimal transfer frequency for a specific arrangement of a given system, which can lead to drastic increases in performance. This has allowed the design of intelligent systems that are able to adaptively tune their frequency in order to achieve maximum efficiency.

The generality of CMT is also another advantage, as many different systems can be analysed using the same standard set of equations; only recalculation of parameters such as the coupling coefficient and loss rates are required to generate performance criteria of characteristically new system.

5.1.2 Circuit Theory (CT)

The concept of CMT, along with its underlying mathematical formulation, is somewhat abstract. Furthermore it has only be employed for basic WPT systems i.e. RLC circuits. For WPT systems that comprise of more advanced topologies, such as systems that include impedance matching circuits, Circuit Theory (CT) is the best choice. By formulating all key electronic parameters within circuit equations obtained by node analysis, two-port networks or otherwise, optimisation of the relevant circuit parameters can be performed to maximise efficiency. CT is an invaluable tool in analysing complete electronic systems that incorporate WPT technology, as the total behaviour of the system can be studied. As long as the circuit components are electrically small, the lumped element approximation that underpins CT allows for an accurate description of the system.

It is also important to point out that formulations of CMT involved in WPT analysis require a basic understanding of CT. Lumped resistance, inductance and capacitance are used to define the coupling coefficient and loss rates. In actuality, the only difference between CMT and CT is the underlying mathematical framework - both techniques describe the same physical mechanism of near-field WPT. Indeed, it has been shown that CT and CMT are equivalent when calculating both the efficiency and optimal load of a resonant WPT system in steady-state [7].

5.1.3 S-Parameters

As system frequency increases, the lumped-element approximation is no longer valid. The distribution of current through the circuit can no longer be assumed as constant, and the flow of power through the circuit is defined in terms of incident and reflected waves. The interaction of a wave at a component boundary may be treated as a two-port network, and a scattering matrix can be constructed to describe the transmission and reflection of the wave. The elements of the matrix are termed Scattering Parameters, or S-Parameters. The difficulty in calculating voltage and current at high-frequencies means that S-Parameters are usually computed numerically via full wave electromagnetic solvers or experimentally by network analysers. Once computed however, the calculation of the transfer efficiency is particularly easy - it is simply equal to the square magnitude of the coefficient that corresponds to the voltage gain. S-Parameters also allow analysis of WPT in the region that is in the near-field but outside the coupling regime, known as the radiating near-field or Fresnel zone. The mixture of radiative and non-radiative effects found in the region, which lies between one-half wavelength and one-wavelength away from the source, renders conventional analysis difficult. Generally speaking, S-Parameters can be applied in any situation involving high-frequency power transmission, including antenna analysis, but their semi-theoretical nature prevents widespread use over CMT or CT for near-field analysis.

5.2 Far-Field

Far-field techniques are applied to WPT system employing electromagnetic radiation as the transfer mechanism. Since the transmitters and receivers that compromise these systems are antennas, Antenna Theory (AT) is used to for their analysis. The key approximation of AT is that the electromagnetic waves are plane-waves, implying that electric and magnetic field constituents are orthogonal. This approximation is know as the far-field approximation and holds for separation distances that are much greater than one wavelength away from the source.

5.2.1 Antenna Theory (AT)

Out of all the modelling techniques, efficiency computation in the far-field is the easiest. The Friis formula (1) expresses the WPT efficiency of two antennas in terms of the path loss and the product of their individual gains [24, Ch4, p. 77].

$$\eta = \underbrace{G_t G_r}_{Gains} \underbrace{\left(\frac{\lambda}{4\pi r}\right)^2}_{Path\ loss} \tag{1}$$

By including additional factors into the original equation, the effects of impedance and polarisation mismatch can be accounted for (equation (1) assumes both impedance and polarisation matching). Its initial simplicity is complicated however as this formula diverges as the separation distance approaches one-wavelength. This is due to the fact that at these distances and below, the electromagnetic radiation takes on a more complex form than plane-wave. This violates the underpinning assumption that allows derivation of the Friis formula (1).

AT provides a geometrically rich description of far-field WPT transfer. The pattern of radiation produced by an antenna acting is dependent upon its operating frequency, shape and size. These key details are all encoded within the expressions for the transmitter and receiver gains. Gain is a term used to evaluate the performance of antennas and compares the radiation pattern of an antenna with a hypothetical antenna that produces a uniform radiation pattern. In addition, it can be shown by the reciprocity theorem that the transmission characteristics of an antenna equally describe how it behaves as a receiver. Due to this link gain is a very important quantity in the engineering of antenna systems. From inspection of equation (1) it is clear that in order to maximise the efficiency for a given frequency, it is necessary to maximise both the transmitter and receiver gains. For this reason, the majority of research in far-field WPT is focussed towards the design of high gain antennas for the development of higher efficiency systems.

What can be concluded about the modelling techniques presented in Sections 5.1 & 5.2 is that their application is restricted based upon their approximations. With the exception of numerical methods, there is no modelling technique that is able to categorise the broad range of possible WPT systems. This produces issues related to accuracy and restriction in terms of separation distance, transmitter/receiver size and frequency. Analysis is particularly difficult for systems that operate around the boundaries of high or low frequencies or in the intermediate region between the near-field and far-field.

6 General Model of WPT

What lies at the heart of efficient WPT is system geometry. In near-field WPT, the coupling coefficient relies solely on geometric parameters such as transmitter size, shape and alignment with a receiver. For far-field systems, the radiation pattern associated with an antenna gives rise to its gain, a key parameter in the Friis transmission equation (1). Due to this fundamental importance, high-efficiency WPT can be realised by manipulating the geometry of the system. Performing a full, geometric based analysis using the modelling techniques described in Section 5 is not possible due to the restriction on separation distance, frequency and electric size. Consequently, a general model is required that avoids these approximations to provide a geometric description of WPT. The development of this model is currently being undertaken at The University of Reading.

The basis of the model lies in identifying that the transportation of energy in WPT takes place through the electromagnetic fields associated with the transmitter and receiver. These fields, although characteristically different for near-field and far-field systems, are the basic ingredient of WPT[3]. Knowledge of the electromagnetic fields, whether numerically or via closed-form solutions, permit the calculation of the Poynting vector which describes the power density associated with the electromagnetic fields. The Poynting vector can be integrated over surfaces around the transmitter and receiver to calculate the power leaving and entering each structure. The efficiency of transfer between the structures can then be calculated and geometric changes made to improve the efficiency. Losses associated with feeding the structure or the transfer of power to a mismatched output load require additional theory, but can be calculated. It is stressed however that although of importance, such losses are not at the forefront of the model since the interest lies in the geometric analysis of the transmitting and receiving structures. Of further note is the need for unrestricted electromagnetic fields, since if the fields are restricted then the model will also suffer the same restriction. For complicated structures, this places a reliance upon numerical methods.

Ideas for future work include: how to incorporate laser-based systems into the model and extending the mathematical formulation to make the model coordinate-free. With the latter it is hoped that the geometric description of WPT can be made as general as possible, thus allowing the analysis of exotic structures which would otherwise be very algebraically-intensive using conventional coordinate systems.

[3]Detailed study of laser based systems require theory beyond that of classical electromagnetism and as such cannot yet be accommodated by the model.

7 Conclusion

The history, applications, physics and modelling techniques behind WPT have presented. The common modelling techniques behind each method of WPT have been described and reviewed in terms of their restrictions and approximations. Motivation for the development of a general model of WPT with which system geometry can be analysed has been presented. The basic theory of this model, as is being developed at The University of Reading, has been introduced.

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