Wireless Energy Transmission

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Introduction

The electrical energy which flows through our infrastructure reaches its destination primarily via the medium of conductive wires. Wireless power dispenses with these artificial connections, instead relying on other phenomena in order to transmit electrical energy. The wireless transmission of electrical energy has lagged behind the advances made in the wireless transfer of information, but the ubiquity of wireless telecommunications has begun to spur renewed interest in liberating devices from wires. Such principles have been known for over a century; a few are in widespread use already. (Rossetti, 2005) Inductive coupling allows the transfer of electrical energy (albeit over a short range) between the separate circuits inside a transformer, and is also the means by which many rechargeable devices are recharged. Recent advances have sought to increase the range over which this process can occur. A more technically challenging method is the use of focused beams of electromagnetic radiation in order to transmit electrical energy. Microwaves, radio waves, and lasers have all been explored with varying degrees of success. Even more exotic methods include the use of the earth's natural conductivity and its atmosphere in order transfer electrical energy. (Wireless Power Planet, 2011)

While wireless telecommunications and wireless power often make use of the same phenomena, they have different technical considerations. Efficient absorption of energy is less critical in telecommunications. What is most important is ensuring that communications signals are clear and distinct. In the case of wireless energy transmission, it is the efficient transfer of energy from the transmitter to the receiver that is of primary importance. (Wireless Power Planet, 2011) Inefficiency has been the greatest technical hurdle faced by researchers attempting to make wireless power economically feasible. Technical possibility has long exceeded financial plausibility, though this is, of course, changing as we speak.

Electromagnetic Induction

The most common device for wireless energy transmission is the humble transformer, which transmits electrical energy between unconnected circuits. The distance separating these circuits is quite limited, but the magnitude of the separation is not the principle utility of a transformer. Their utility is instead found in their ability to increase or decrease the voltages of electricity transferred between the circuits. A ubiquitous use of transformers is in power grids. Power grids must transmit electrical energy at extremely high voltages to reduce the inefficiency of transfer over kilometers of wires. Power dissipated by the wires is a product of resistance and the square of the current, so electricity is transmitted most efficiently when it is high-voltage but low-current. When it comes time to transfer the electrical energy to substations, and from there to residences and businesses, transformers step down the voltage to make it suitable for use. (Schmitt, 2002)

Transformers function because of Faraday's law of magnetic induction. The simplest form of the device consists of two coils of wire spaced closely together but distinctly separated. These coils are usually wrapped around a magnetically permeable core (such as an iron ring) that channels the magnetic field as it passes from one coil through the other, thus maximizing the amount of magnetic flux through the coils. In the primary coil, a changing current flows through the wires and generates a magnetic field. A portion of the primary coil's magnetic field will then pass through the secondary coil. Because the current, and hence the magnetic field, in the primary coil is changing with time, the magnetic flux experienced in the secondary coil is also changing. If the secondary coil is then connected to a load, electromotive force (a voltage) is created in the circuit, and current flows from the primary to the secondary circuit. By this method, electrical energy is transmitted without need of a direct connection between the circuits. (Schmitt, 2002)

As previously stated, the primary utility of transformers does not derive from the distance over which they transfer current, as this distance is quite small, but some devices do focus on the use of magnetic induction to transmit electrical energy. These devices typically eschew the fixed placement of the circuits, as in a transformer. (Cannon, 2009) The range is still limited, and efficiency is lost due to the looser placement of the circuits in relation to each other (they suffer from decreased coupling coefficient), but there are occasions where they are still far more suitable than wired systems. One advantage they have is safety. Wires can be affected by wear, corrosion, and contaminants. If energy is instead transmitted through magnetic fields, there is a reduced risk of electrocution when working with high power systems. Sparks become less common, a concern in volatile environments such as coal mines. (Coup, 2003) Electric toothbrushes and shavers are another example where induction is chosen for safety's sake. Since these devices are often in contact with water, an induction charger allows the contacts on the battery to be fully covered, thus keeping the user safe from electricity. Induction cookers use induction to directly heat cookware by placing a coil under a ceramic range, and then driving current into ferromagnetic cookware. Such cookers have an advantage over gas and electric cookers in both energy efficiency and safety, as the range itself remains cool while only the pot or pan is heated. (Wireless Power Planet, 2011)

Induction is also useful in cases where wires are clumsy or cumbersome. Some mobile phones and similar devices can be charged by placing them on a convenient pad instead of directly connecting them to a wall charger. (Schneider, 2010) Induction is ideal for powering vehicles that move along fixed tracks. Wireless vehicles are in use in some manufacturing facilities to transport materials along the factory line. Research is also being conducted on a use for induction in powering electric automobiles. Beyond allowing an electric car to charge itself by resting on a charging pad, akin to the earlier mentioned pads for charging consumer electronics, researchers are investigating using the roads themselves as chargers by installing induction coils into them. Such systems could also tie into plans for automated traffic control schemes, thus allowing cars to drive themselves. (Michler, 2012) Since the early 1960's, inductive coupling has been increasingly used to power implanted medical devices, such as pacemakers and artificial hearts. More recently, radio frequency smart cards and tags also make use induction. (Giler, 2009)

An additional advantage of inductive coupling is that it allows device to eschew the use of batteries. Batteries suffer from a multitude of limitations. They are typically heavier than the receiving coils required for inductive coupling, and are thousands of time less efficient than even passable inductive resonance systems. Batteries are expensive to manufacture and require increasingly rare and hazardous components. Their composition presents problems in disposal and recycling, since most battery chemicals are poisonous or corrosive to some degree. They are a pernicious contributor to the problem of electronic waste. (Giler, 2009)

Simple induction is typically unsuitable for transmitting power over distances greater than the size of the primary coil. The omission of a magnetic core greatly decreases transfer efficiency. However, this liability can be addressed using resonant inductive coupling (also called electrodynamic induction). In this scheme, each circuit includes not just a coil (an inductor) but also a capacitor, thus forming what is called an LC circuit. In the simplest LC circuit, energy is stored in the electric field between the capacitor's plates and alternatively in the magnetic field of the inductor. A fully charged capacitor will begin to discharge through the inductor, which produces a magnetic field, and when the voltage across the capacitor drops to zero the magnetic field will also begin to collapse. This induces a voltage across the capacitor, which then begins to charge, but with a polarity opposite to its original configuration. In the idealized form of the circuit, the process continues back and forth, electrical energy oscillating between the magnetic and electric field at a frequency which depends on the construction of the circuit. In reality, resistance takes its toll on the flow of energy, but the oscillation can be maintained as long as there is a continuous alternating current feeding the circuit. (Integrated, 2003) In electrodynamic induction, the coils of the primary and secondary circuit are designed to resonate at a similar frequency. When so tuned, power can be transmitted between the circuits at increased ranges, usually multiples of the size of the coils. Provided that the secondary coil can capture more the of energy held in the oscillating fields than is lost with each cycle, then electrodynamic induction is also quite efficient. (Karalis, 2008)

Tesla coils are a celebrated example of a resonant inductively coupled device, specifically a resonant transformer. It has a much lower coupling coefficient (the degree to which the magnetic field of the primary coil pass through the secondary coil, measured from zero to one) than a conventional transformer. A conventional transformer has a coupling coefficient that approaches one, because the magnetic field is usually confined to a magnetically permeable core. Due to the loose coupling and the air gap between the coils in a Tesla coil, the coupling coefficient is closer to 0.2. By comparison, modern electrodynamic induction devices can have coupling coefficients as low as 0.01. (Finkenzeller, 2010)

Electromagnetic Radiation

Electromagnetic radiation makes use of the far field region of an electromagnetic field, as opposed to the near field region employed by electrodynamic induction. Instead of flowing out in all directions, radiation can be focused into a beam that delivers nearly all of its energy from the transmitter to the receiver. These distances are measured not in meters, but in kilometers. Though theoretically conceived near the end of the nineteenth century, power beaming (as the technology is also known by) would not be effectively implemented until the middle of the twentieth century. Early progress was hampered by an inability to produce beams at concentrations sufficient enough to transmit meaningful amounts of energy. The development of microwave transmitters, and then later, lasers, allowed the creation of the first functional power beaming systems. (Brown, 1984)

Microwave power transmission systems were the first to be developed. World War II spurred the development of microwave generators as an outgrowth of radar research. No serious attempt was made to exploit microwaves for power transmission because their power handling capabilities were still limited. More importantly, although electrical energy could be transformed into microwaves by a magnetron, no apparatus had yet been developed to allow microwaves to be reconverted into electrical energy. This was resolved with the invention of the rectenna, a combination of an antenna and a rectifier. Microwaves induce alternating current in the antenna, and the rectifier changes the induced alternating current into a direct current. (Brown, 1984)

Interest in microwave power transmission has leveled off since the 1980s, though several successes have been reported. A miniature helicopter powered by microwaves was successfully test flown in 1964. (Brown, 1984) Other experimental vehicles have included airplanes, rovers, and balloon platforms. Transmission at distances of over a hundred kilometers has been reported, and power has been transmitted between space borne objects. Japan has active plans to develop a space-to-ground microwave transmitter that should power over 300,000 homes. (Covert, 2009)

Microwave systems suffer from a few disadvantages, some of which are common to all power beaming methods, and some which are unique to microwaves. One disadvantage shared by all beaming technologies is the need for an uninterrupted line of sight between the transmitter and the receiver. This is, of course, the trade-off for the massive improvement in ranges versus near field methods, which despite their short ranges do not depend on line of sight. Beams are also susceptible to dispersion even in a vacuum. In an atmosphere, the effect is more pronounced. This dispersion has to be compensated for by relatively large transmitters and receivers, which can be expensive and difficult to engineer. An effect known as the thinned-array curse limits the ability to use multiple, smaller transmitters instead of fewer, larger transmitters to propagate a cohesive beam. This frustrates attempts to design handier machinery. The problem of size leads to a criticism of microwave systems in particular. The behavior of both microwave emitters and lasers is affected by the Raleigh criterion. Essentially, the cohesion of a beam is dependent on the relationship in size between the transmitter element (an antenna for a microwave, and an aperture for a laser) and the wavelength of the beam, so while large transmitter elements will lead to a more cohesive beam, smaller elements will decrease cohesiveness proportionally. Since microwaves have longer wavelengths than the visible portion of the electromagnetic spectrum, microwave machinery needs to be correspondingly larger than laser devices for the same level of beam cohesion. This difference has been the primary driver for laser power beaming. Besides requiring smaller receivers and transmitters, laser beams also have a greater energy density than microwaves, which offsets the lower conversion efficiency of most lasers. (Summerer, 2008)

For these reasons, the current focus in power beaming has shifted to lasers, with bulky antennas giving way to beam emitters, and rectennas replaced with photovoltaic panels. Lasers also have the advantage that, being composed of visible light, they cannot potentially interfere with radio communications devices as microwaves might. With microwave network density showing no signs of decrease, this is an important consideration. (Wojtkowiak , 2004) As with microwaves, small laser powered vehicles have been constructed by various organizations. NASA and other space agencies are actively investigating the use of lasers for a variety of purposes: powering extraterrestrial rovers, satellites, and high altitude unmanned aircraft. The Spaceward Foundation currently sponsors a contest to develop laser beaming systems to power tether climbers, vehicles meant to traverse the cables connecting earth to the orbital portion of a space elevator. Payloads have been elevated to the height of one kilometer at velocities of nearly four meters per second. (Spaceward, 2008)

The most expansive use for laser power beaming yet envisioned has nothing to do with transmitting energy into space, but instead the opposite. Though solar power is becoming more widespread as component costs and solar cell efficiency continue to rise, it still suffers from terrestrial concerns: atmosphere, weather, the day/night cycle, and lack of available real estate. Orbital placement alleviates all these concerns. Solar cells would no longer have to worry about nighttime, cloudy days, or finding land convenient for establishing solar farms. Power generated by the photovoltaics could then be beamed to receiving stations on earth, and from there to wherever it is needed. Though microwave methods have been considered for transmission from the solar arrays, lasers, as mentioned before, would be less bulky. Various kinds of laser have been proposed for these platforms, but the solar pumped laser is the most competitive laser design. Despite being less efficient by themselves than other varieties, such as solid-state lasers, solar pumped lasers do not require an external electrical source for the lasing mechanism. This avoids the need to convert solar energy into electricity on the satellite, then to use it to power the laser, and then finally convert the laser back into electrical energy at the ground level. Inefficiencies in conversion processes compound across the system, so reducing the number of processes is always helpful. Laser power beaming suffers from more inefficiencies than microwaves, both from the conversion of energy into laser beams and the absorption from solar panels, but, as mentioned earlier, they have their compensations. (Summerer, 2008)

The orbital solar power idea has several other engineering hurdles to overcome. Materials must be lifted into space at great cost, a factor which the aforementioned tether climbers hope to rectify. Afterwards the arrays must be assembled and maintained. This labor too must be imported. Space is inhospitable for life, and it is not overly kind to machinery either. Radiation, solar storms, micro meteors, and man-made space litter can all conspire to wreck solar panels, and they can generally shorter service lifetimes than their terrestrial counterparts. This affects the economic viability of orbital solar array placement. (Ortner, 2010)

Electromagnetic Conduction

Regular power lines can be designed to reduce their dependence on wires. Single wire earth return transmission lines eschew additional wires and do not require a neutral line to serve as a return path. Instead, the earth itself serves as the return path and completes the circuit by linking one ground to another. While slightly inefficient compared to traditional transmission lines, they have numerous advantages. Construction and materials costs for single wire earth return systems are usually at least half that of two and three wire systems, so they are commonly seen in rural electrification projects. They are generally more reliable than traditional systems and are more easily constructed with the resources and expertise available in developing nations.

Despite the current flowing in the earth, being near the grounds presents no danger of electrocution. However, if placed in an area of heavy resistance, the grounding poles can suffer from heat damage and burn out, so proper placement is important. Unlike multi-wire transmission systems, single wire systems are incapable of clashing with other wires, thus removing a source of system damage and possibly wildfires, both of which are great concerns in rural areas. (Holland, 2008)

Some exotic power transmission systems still use conductive elements but dispense completely with wires. The most famous example is the World Wireless System conceived of by Nikola Tesla. The never completed Wardenclyffe Tower was intended to be the base of this system, which would transmit both information and energy wirelessly. (Schneider, 2010) The mechanisms by which the tower would accomplish its goals were expounded upon by Tesla, though they remain, perhaps deliberately, obscure. Though sound theoretically, there has been little attempt to follow up on Tesla's work, and an implementation the design as originally described may unfortunately be impractical. (Bradford, 2011)

The World Wireless System would have made use of one or both of the following avenues of conductivity: the upper atmosphere and the earth itself. In a manner analogous to that of the single wire system described earlier, great towers would have been erected to link the earth and upper atmosphere. Tesla coil transmitters would ionize a path (via the generation of plasma) to the upper troposphere along which current would flow, following a reciprocal path generated at a receiver tower. In effect, the atmosphere would serve as the single wire. Like wired power transmission systems, the atmospheric electricity would be of extreme voltages to minimize dissipation over a distance. The earth component of the system is described as propagating oscillating electromagnetic waves within the earth, making it behave in fashion similar to an LC circuit. In this way, the earth resonance portion behaves both like an electrodynamic inductor using the earth as a medium, as well as conducting like the ground path in a single wire return system. (Bradford, 2011)

The precise mechanisms behind Tesla's design remain ill-understood, and there are competing ideas about the possible theories by which he intended to achieve his end of trans-Atlantic power transmission. Little attempt has been made to replicate his more grandiose experiments due to the engineering hurdles that were discovered during the original construction of the Wardenclyffe Tower. To be practical, truly stupendous amounts of energy would be required. The literature mentions that the elevated terminal for one of the towers would need to be charged to about 100 million volts. The World Wireless System is likely to be left as an inspiring, albeit impractical, milestone in the history of science. (Bradford, 2011)

Conclusion

Wireless methods of power transmission offer an incredible amount of utility, accompanied by hefty engineering challenges. Still, the potential rewards have motivated over a century of research, and progress up to now has proved reasonably satisfactory. The explosion of wireless telecommunications technology continues to spur development as consumers and researchers yearn for equally dramatic results with wireless energy transfer. As the world continues to electrify, wireless methods will probably see wider use, given that they have the potential to be less expensive than wired systems. Power may soon be transmitted, if not from orbital solar arrays, then at least across the living room.

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