Lecture 8: Supply Systems- Wireless Power Transmission

8.1 Introduction

Wireless power transfer (WPT), wireless power transmission, wireless energy transmission (WET), or electromagnetic power transfer is the transmission of electrical energy without wires as a physical link. In a wireless power transmission system, a transmitter device, driven by electric power from a power source, generates a time-varying electromagnetic field, which transmits power across space to a receiver device, which extracts power from the field and supplies it to an electrical load. Wireless power transfer is useful to power electrical devices where interconnecting wires are inconvenient, hazardous, or are not possible.

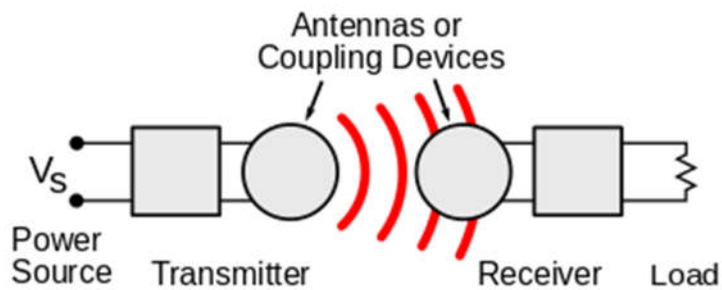

Figure 8.1 Generic block diagram of a wireless power system.

Wireless power techniques mainly fall into two categories,

- Near field and
- Far-field.

8.2 Near field Transfer

In near field or non-radiative techniques, power is transferred over short distances by magnetic fields using inductive coupling between coils of wire, or by electric fields using capacitive coupling between metal electrodes. Inductive coupling is the most widely used wireless technology; its applications include charging handheld devices like phones and electric toothbrushes, RFID tags, and wirelessly charging or continuous wireless power transfer in implantable medical devices like artificial cardiac pacemakers, or electric vehicles.

In fact a transformer is transferring energy wirelessly through magnetic field coupling, although it was invented more than 100 years ago. But if you remove the iron core and move the two coils apart, the transfer efficiency drops drastically. That is why the two coils must be put close enough to each other.

However, if the transmitter and receiver coils have the same resonant frequency, which is determined by the material and shape of the coil, transfer efficiency will decrease much more slowly when they are moved apart. A group from MIT, led by Prof. Marin Soljacic has succeeded in transferring electric energy (60 Watt) between two coils more than two meters apart through non-radiative electromagnetic field, as shown in Figure 8.2

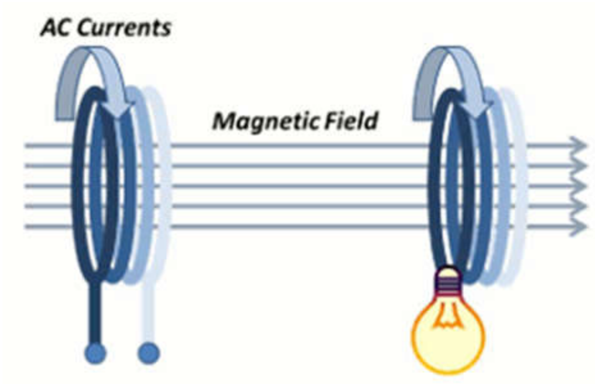

Figure. 8.2: Transferring energy through magnetic field coupling between two coils with identical resonant frequency.

Since near field transfer is usually working at 50 or 60Hz, there is almost no interference with TV, radio or Wi-Fi signals. The major concern is the possible influence on human health. Luckily, almost all materials that form human body are non-magnetic, so they interact very weakly with magnetic field, even to several Tesla like that in a modern MRI machine. Thus, such magnetic-field-based transfer is quite safe to people within the transfer range.

8.3 Far-field Transfer

In far-field or radiative techniques, also called power beaming, power is transferred by beams of electromagnetic radiation, like microwaves or laser beams. These techniques can transport energy longer distances but must be aimed at the receiver. Proposed applications for this type are solar power satellites, and wireless powered drone aircraft.

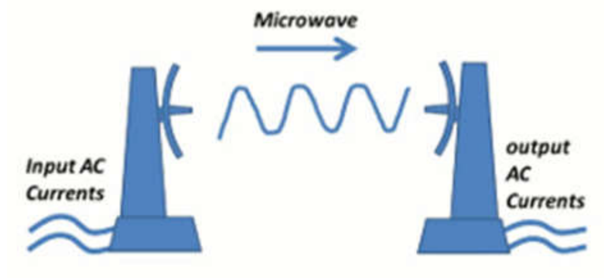

Figure.8.3: Transferring energy through microwave between two stations.

In the early times, experiments were carried out with radio and microwaves, around 1GHz. Electric energy is transferred to a strong beam of radio or microwave by a dish-like antenna, travels through the atmosphere and then received by another antenna which transfers it back to AC electric current, as shown in Figure 8.3.

Yet according to diffraction, the longer the wavelength is, the larger the antennas must be in order to achieve sufficient directionality. Since speed of light in the air is about 3×10^8 m/s, the corresponding wavelength of radio and microwaves used is about one meter, which requires an antenna with a dimension of several meters to several kilometers. Thus we have to use electromagnetic waves with shorter wavelength if we want to transfer energy to smaller objects. Moreover, since the electromagnetic wave used lies in the waveband of radio, TV, cell phone and Wi-Fi, with a signal intensity several order-of-magnitude larger, you probably won't want it any close to residences or offices.

8.4 Transfer via Laser

Benefiting from advanced technology in both solid-state lasers and photovoltaic cells (notice that monochromatic photovoltaic cells are more efficient than ordinary solar cells) today, converting energy into laser beams to transfer over long distances is becoming closer to practice. NASA has made a model plane powered by a laser beam focused on a panel of photovoltaic cells on its ventral, see Figure 8.4. Comparing to radio and microwaves, laser has many advantages like short wavelength (shorter than several micrometers), good beam width, perfect directionality and non-interference with radio, TV, cell phone or Wi-Fi signals. But it still has many drawbacks, like relatively lower efficiency during conversion and atmospheric absorption.

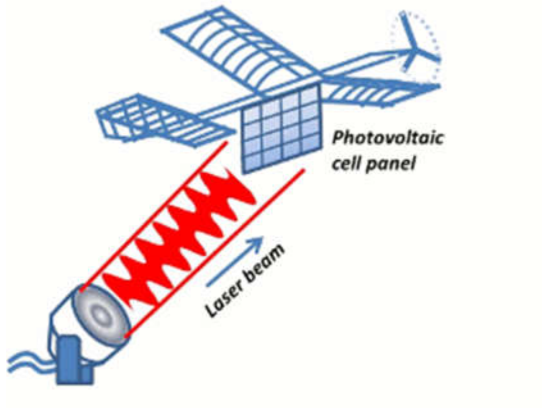

Figure.8.4: Diagram of NASA's model plane powered by an infrared ground-based laser beam centered at the photovoltaic cell panel on its ventral.

An important issue associated with all wireless power systems is limiting the exposure of people and other living things to potentially injurious electromagnetic fields.

In general a wireless power system consists of a "transmitter" device connected to a source of power such as a mains power line, which converts the power to a time-varying electromagnetic field, and one or more "receiver" devices which receive the power and convert it back to DC or AC electric current which is used by an electrical load. At the transmitter the input power is converted to an oscillating electromagnetic field by some type of "antenna" device. The word "antenna" is used loosely here; it may be a coil of wire which generates a magnetic field, a metal plate which generates an electric field, an antenna which radiates radio waves, or a laser which generates light. A similar antenna or coupling device at the receiver converts the oscillating fields to an electric current. An important parameter that determines the type of waves is the frequency, which determines the wavelength.

8.6 Tesla's Dream

Nikola Tesla, the eccentric genius for whom two modern electric vehicle companies have been named, envisioned a wireless power grid that could transmit electrical energy through the air. Although his idea is technically feasible, it turns out to be highly inefficient over long distances. It's fine for wireless communication, where a massive transmitting antenna pumps out thousands of watts over many kilometers to radio receivers that only need to gather a few milliwatts of the signal - about one one-millionth of the power transmitted. But if you scale that up to an antenna delivering several thousand watts to each home in a city, you can see how insanely powerful the transmitter would have to be, not to mention the unacceptable inefficiency of the whole system.

On the other hand, energy transfer can achieve 90% efficiency when the distance is very small, making Tesla's concept of inductive coupling perfectly fine for delivering power to passive RFID tags and IoT devices that don't have batteries, as well as charging personal electronics and even electric vehicles.

Table 8.1 Different wireless power technologies

Technology	Range	Directivity	Frequency	Antenna devices	Current and/or possible future applications
Inductive coupling	Short	Low	Hz – MHz	Wire coils	Electric tooth brush and razor battery charging, induction stovetops and industrial heaters.
Resonant inductive coupling	Mid-	Low	kHz – GHz	Tuned wire coils, lumped element resonators	Charging portable devices (Qi), biomedical implants, electric vehicles, powering buses, trains, MAGLEV, RFID, smartcards.
Capacitive coupling	Short	Low	kHz – MHz	Metal plate electrodes	Charging portable devices, power routing in large-scale integrated circuits, Smartcards, biomedical implants.
Magnetodynamic coupling	Short	N.A.	Hz	Rotating magnets	Charging electric vehicles, biomedical implants.
Microwaves	Long	High	GHz	Parabolic dishes, phased arrays, rectennas	Solar power satellite, powering drone aircraft, charging wireless devices
Light waves	Long	High	≥THz	Lasers, photocells, lenses	Charging portable devices, powering drone aircraft, powering space elevator climbers.

8.7 Timeline of history of the transmission of wireless energy

- **1820**: André-Marie Ampère describes Ampere’s law showing that electric current produces a magnetic field.
- **1831**: Michael Faraday describes Faraday’s law of induction, an important basic law of electromagnetism.
- **1864**: James Clerk Maxwell synthesizes the previous observations, experiments and equations of electricity, magnetism and optics into a consistent theory, andmathematically models the behavior of electromagnetic radiation.
- **1888**: Heinrich Rudolf Hertz confirms the existence of electromagnetic radiation. Hertz’s "apparatus for generating electromagnetic waves" is generally acknowledged as the first radio transmitter.
- **1891**: Nikola Tesla improves on Hertz's primitive radio-frequency power supply in U.S. Patent No. 454,622, "System of Electric Lighting."
- **1893**: Nikola Tesla demonstrates the illumination of phosphorescent bulbs wirelessly (without any wires connected to the bulbs) at the World's Columbian Exposition in Chicago.[citation needed].
- **1894**: Hutin & LeBlanc, espouse long held view that inductive energy transfer should be possible, they file a U.S. Patent describing a system for power transfer at 3 kHz.
- **1894**: Nikola Tesla wirelessly lights up vacuum tubes at the 35 South Fifth Avenue laboratory, and later at the 46 E. Houston Street laboratory in New York City by means of "electrodynamic induction."
- **1894**: Jagdish Chandra Bose ignites gunpowder and rings a bell at a distance using electromagnetic waves, showing that communications signals can be sent without using wires.
- **1895**: Jagdish Chandra Bose transmits signals over a distance of nearly a mile.
- **1896**: Nikola Tesla transmits signals over a distance of about 48 kilometres (30 mi).
- **1897**: Guglielmo Marconi uses Hertz's radio transmitter to transmit Morse code signals over a distance of about 6 km.
- **1897**: Nikola Tesla files the first of his patent applications dealing with wireless transmission.
- **1899**: In Colorado Springs Nikola Tesla writes, "the inferiority of the induction method would appear immense as compared with the disturbed charge of ground and air method."
- **1900**: Guglielmo Marconi fails to get a patent for radio in the United States.
- **1901**: Guglielmo Marconi first transmits and receives signals across the Atlantic Ocean using Tesla's wireless transmitter.
- **1902**: Nikola Tesla vs. Reginald Fessenden} U.S. Patent Interference No. 21,701. System of Signaling (wireless); selective illumination of incandescent lamps, time and frequency domain spread spectrum telecommunications, electronic logic gates in general.
- **1904**: At the St. Louis World's Fair, a prize is offered for a successful attempt to drive a 0.1 horsepower (75 W) air-ship motor by energy transmitted through space at a distance of least 100 feet (30 m).
- **1917**: The Wardenclyffe tower is demolished.
- **1926**: Shintaro Uda and Hidetsugu Yagi publish their first paper on Uda's "tuned high-gain directional array" better known as the Yagi antenna.
- **1961**: William C. Brown publishes article that explores possibilities of microwave power transmission.
- **1964**: William C. Brown demonstrated on CBS News with Walter Cronkite a microwave-powered model helicopter that received all the power needed for flight from a microwave beam. Between 1969 and 1975 Brown was technical director of a JPL Raytheon program that beamed 30 kW over a distance of 1 mile at 84% efficiency.

- **1968**: Peter Glaser proposes wirelessly transferring solar energy captured in space using "Powerbeaming" technology.
- **1971**: Prof. Don Otto develops a small trolley powered by induction at The University of Auckland, in New Zealand.
- **1973**: World first passive RFID system demonstrated at Los-Alamos National Lab.
- **1975**: Goldstone Deep Space Communications Complex does experiments in the tens of kilowatts.
- **1988**: A power electronics group led by Prof. John Boys at The University of Auckland in New Zealand, develops an inverter using novel engineering materials and power electronics and conclude that inductive power transmission should be achievable. A first prototype for a contact-less power supply is built. Auckland Uniservices, the commercial company of The University of Auckland, Patents the Technology.
- **1989**: Daifuku, a Japanese company, engages Auckland Uniservices Ltd to develop the technology for car assembly plants and materials handling providing challenging technical requirements including multiplicity of vehicles.
- **1990**: Prof. John Boys team develops novel technology enabling multiple vehicles to run on the same inductive power loop and provide independent control of each vehicle. Auckland UniServices Patents the technology.
- **1996**: Auckland Uniservices develops an Electric Bus power system using Inductive Power Transfer to charge (30-60kW) opportunistically commencing implementation in New Zealand. Prof John Boys Team commission 1st commercial IPT Bus in the world at Whakarewarewa, in New Zealand.
- **2004**: Inductive Power Transfer used by 90 per cent of the US$1 billion clean room industry for materials handling equipment in semiconductor, LCD and plasma screen manufacture.
- **2005**: Prof Boys' team at The University of Auckland, refines 3-phase IPT Highway and pick-up systems allowing transfer of power to moving vehicles in the lab
- **2007**: A physics research group, led by Prof. Marin Soljačić, at MIT confirm the earlier (1980's) work of Prof. John Boys by wireless powering of a 60W light bulb with 40% efficiency at a 2 metres (6.6 ft) distance using two 60 cm-diameter coils.
- **2008**: Bombardier offers new wireless transmission productPRIMOVE, a power system for use on trams and light-rail vehicles.
- **2008**: Industrial designer Thanh Tran, at Brunel University made a wireless light bulb powered by a high efficiency 3W LED.
- **2008**: Intel reproduces Nikola Tesla's 1894 implementation and Prof. John Boys group's 1988's experiments by wirelessly powering a light bulb with 75% efficiency.
- **2008:** Greg Leyh and Mike Kennan of the Nevada Lightning Laboratory publish a paper on the disturbed charge of ground and air method of wireless power transmission with circuit simulations and test results showing an efficiency greater than can be obtained using the electrodynamic induction method.
- **2009:** Powermat Technologies introduced wireless charging systems, that work with a combination of radio-frequency identification (RFID) and electromagnetic induction.
- **2009:** Palm (now a division of HP) launches the Palm Pre smartphone with the Palm Touchstone wireless charger.
- **2009:** A Consortium of interested companies called the Wireless Power Consortium announce they are nearing completion for a new industry standard for low-power (which is eventually published in August 2010) inductive charging.
- **2009:** An Ex approved Torch and Charger aimed at the offshore market is introduced. This product is developed by Wireless Power & Communication, a Norway based company.

- **2009:** A simple analytical electrical model of electrodynamic induction power transmission is proposed and applied to a wireless power transfer system for implantable devices.
- **2009:** Lasermotive uses diode laser to win $900k NASA prize in power beaming, breaking several world records in power and distance, by transmitting over a kilowatt more than several hundred meters.
- **2009:** Sony shows a wireless electrodynamic-induction powered TV set, 60 W over 50 cm
- **2010:** Haier Group debuts "the world's first" completely wireless LCD television at CES 2010 based on Prof. Marin Soljacic's follow-up research on the 1894 electrodynamic induction wireless energy transmission method and the Wireless Home Digital Interface (WHDI).
- **2010:** System On Chip (SoC) group in University of British Columbia develops a highly efficient wireless power transmission systems using 4-coils. The design is optimized for implantable applications and power transfer efficiency of 82% is achieved.
- **2012:** A group at University of Toronto, presented for the first time a closed form analytical solution for the optimum load that achieves the maximum possible wireless power transfer efficiency under arbitrary input impedance conditions based on the general two-port parameters of the network. The proposed method effectively decoupled the design of the inductive coupling two-port from the problem of loading and power amplifier design.
- **2012:** "Bioelectromagnetics and Implantable Devices" group in University of Utah, USA develops an efficient resonance based wireless power and data transfer system for biomedical Implants. Presented design achieves more than twice the efficiency and frequency bandwidth compared to conventional inductive link approach. Design approach is extendable to other industrial "smart" wireless power transfer system.
- **2012:** Christopher Tucker, Kevin Warwick and William Holderbaum of the University of Reading, UK develop a highly efficient, compact power transfer system safe for use in human proximity. The design is simple and uses only a few components to generate stable currents for biomedical implants. It resulted from research that directly attempted to extend Tesla's 1897 wireless power work.
- **2013:** Resonance based multi-coil wireless power transfer system is proposed to reduce the variation in power transfer efficiency and data bandwidth with coupling variation. Such systems can compensate the effect of coil misalignment on system performance.
- **2013:** A fully integrated wireless power receiver is demonstrated in CMOS process by a group at University of Toronto. The designed prototype requires no off-chip components or post-processing steps. The demonstrated single-chip prototype is only a few millimeters on each side, mass producible and heavily reduces the cost. This level of integration also enables new possibilities for disposable lab-on-chip solutions.
- **2013:** The concept of a virtual waveguide controlled by ordered magnetic fields for wireless power transmission is proposed.
- **2014:** The first microfluidic implant coil is proposed for the wireless power transfer to the flexible telemetry system. The work demonstrates a soft and flexible coil fabricated with a liquid metal alloy encased in a biocompatible elastomeric substrate to target the application of biomedical implantable devices.
- **2014:** Using compact size metamaterials, power transfer efficiency is enhanced for the wireless powered systems. The proposed applications include short-range wireless power transfer to biomedical implants and wireless charging.

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