

HIGHLY RESONANT WIRELESS POWER TRANSFER IN SUBSEA APPLICATIONS

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Abstract

Recent technological advances have allowed unmanned underwater vehicles to act with more autonomy, allowing them to embark on longer missions to increasingly deeper and more difficult environments. While these vehicles can navigate themselves as they collect and process data, human intervention is still required to replenish their power supplies. Truly autonomous long-duration missions will likely be difficult until the energy sources in these vehicles can be replenished without human intervention. WiTricity Corporation has been developing wireless and automatic charging solutions in a variety of markets, including investigating the feasibility using Highly Resonant Wireless Power Transfer (HR-WPT) technologies to support the transfer of several kilowatts of power wirelessly to a vehicle such as an unmanned underwater vehicle (UUV).

Highly resonant wireless power transfer can enable power transfer through a variety of

materials, including saltwater. A HR-WPT system, encased in a hermetically sealed enclosure, could transfer several kilowatts of power through water while eliminating the need for failure prone wet-mate connectors. Additionally, because HR-WPT systems can transfer power efficiently to devices as they move around, devices such as UUVs could be recharged simply by floating alongside a dock or other platform that has been outfitted with a wireless power source. The high efficiency wireless power transfer between sources and devices with varying relative positions and orientations removes the need for tight mechanical coupling and allows for power to be transferred between objects underwater safely, reliably, and efficiently.

Introduction

Since its founding, WiTricity Corporation has developed and commercialized systems to wirelessly power and recharge a wide variety of devices, ranging from surfaces that can recharge mobile phones at 5-10 W,

to systems that can transfer 3.3 kW to charge electric vehicles. Examples of these systems can be found in Figures 1 and 2. Based on our discussions with users in the community, it appears there is an opportunity to leverage WiTricity's work in HR-WPT to recharge and power vehicles and other equipment underwater.

In addition to discussing the underlying technology behind HR-WPT, this document will show modeling results of predicted performance for an example subsea application.



Figure 1: Photograph of a highly resonant wireless power transfer system used to wirelessly charge a battery in a smart phone (~5 W supplied wirelessly)



Figure 2: Photograph showing an application of HR-WPT for charging full electric and hybrid vehicles.

Background

The idea of transmitting power through the air has been around for over a century, with Nikola Tesla's pioneering ideas and experiments perhaps being the most well-known early attempts to do so¹. He had a vision of wirelessly distributing power over large distances using the earth's ionosphere. Most approaches to wireless power transfer use an electromagnetic (EM) field of some frequency as the means by which the energy is sent. At the high frequency end of the spectrum are optical techniques that use lasers to send power via a collimated beam of light to a remote detector where the received photons are converted to electrical energy. Efficient transmission over large distances is possible with this approach; however, complicated pointing and tracking

¹ Nicola Tesla, "The transmission of electrical energy without wires", *Electrical World and Engineer*, March 1905. <http://www.tfcbooks.com/tesla/1904-03-05.htm>, (acc. Dec. 08).

mechanisms are needed to maintain proper alignment between moving transmitters and/or receivers. In addition, objects that get between the transmitter and receiver can block the beam, interrupting the power transmission and, depending on the power level, possibly causing harm. At microwave frequencies, a similar approach can be used to efficiently transmit power over large distances using the radiated EM field from appropriate antennas². However, similar caveats about safety and system complexity apply for these radiative approaches.

It is also possible to transmit power using non-radiative fields. As an example, the operation of a transformer can be considered a form of wireless power transfer since it uses the principle of magnetic induction to transfer energy from a primary coil to a secondary coil without a direct electrical connection. Inductive chargers, such as those found commonly in electric toothbrushes, operate on this same principle. However, for these systems to operate efficiently, the primary coil (source) and secondary coil (device) must be matched in size and shape to one another, located in very close proximity (within a few millimeters) and carefully aligned with respect to one another. From a technical point of view, this means the magnetic coupling between the source and device coils must be large for proper operation.

But what about going over somewhat larger distances or having more freedom in positioning the source and device relative to each other? That's the question that a group at the Massachusetts Institute of Technology asked themselves. They explored many techniques for transmitting power over "mid-range" distances and arrived at a non-radiative approach that uses resonance to enhance the efficiency of the energy transfer.

High quality factor resonators enable efficient energy transfer at lower coupling rates, i.e., at greater distances and/or with more positional freedom than is otherwise possible (and therefore, this approach is sometimes referred to as "highly resonant" wireless energy transfer or "highly resonant" wireless power transfer). The MIT team demonstrated the highly resonant technique using a magnetic field to transfer energy over a mid-range distance of 2 meters, and an industry was born. In some instances, this technology is also referred to as "magnetic resonance", and it is often contrasted to "induction" for its ability to efficiently transfer power over a range of distances and with positional and orientational offsets. Since that initial demonstration, the use of HR-WPT, or magnetic resonance, has enabled efficient wireless energy transfer in a wide range of applications that was not possible before.

Description of a Typical HR-WPT system

Across an application space that spans power levels from less than a watt to multiple kilowatts, a wireless energy transfer

² William C. Brown, "The history of power transmission by radio waves", *Microwave Theory and Techniques*, IEEE Transactions, 32(9):1230-1242, September 1984.

system based on HR-WPT often has a common set of functional blocks. A general diagram of such a system is shown in Figure 3.

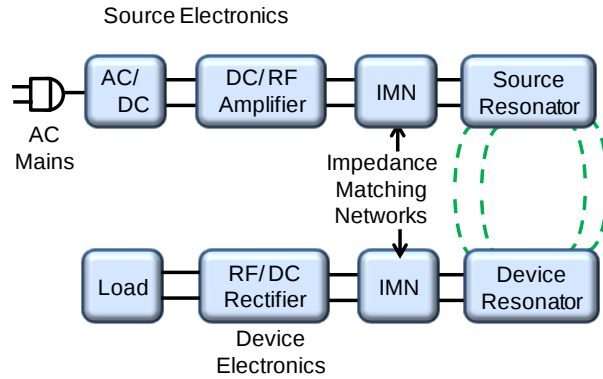


Figure 3: Block diagram of a highly-resonant wireless power transfer system.

Progressing from left to right on the top line of the diagram, the input power to the system is usually either wall power (AC mains) which is converted to DC in an AC/DC rectifier block, or alternatively, a DC voltage directly from a battery or other DC supply. In high power applications a power factor correction stage may also be included in this block. A high efficiency switching amplifier converts the DC voltage into an RF voltage waveform used to drive the source resonator. Often an impedance matching network (IMN) is used to efficiently couple the amplifier output to the source resonator while enabling efficient switching-amplifier operation. Class D or E switching amplifiers are suitable in many applications and generally require an inductive load impedance for highest efficiency. The IMN serves to transform the source resonator impedance, loaded by the coupling to the device resonator and output load, into such an impedance for the source

amplifier. The magnetic field generated by the source resonator couples to the device resonator, exciting the resonator and causing energy to build up in it. This energy is coupled out of the device resonator to do useful work, for example, directly powering a load or charging a battery. For loads requiring a DC voltage, a rectifier converts the received AC power back into DC.

In high power applications, such as charging of plug-in hybrid vehicles, end-to-end efficiencies (AC input to DC output) greater than 90% have been demonstrated. Such efficiencies require that each stage in the system have an efficiency at 97-98% or greater. Careful design in each stage is required to minimize losses in order to achieve such performance.

Physics of HR-WPT: Resonance

Resonance is a phenomenon that occurs in nature in many different forms. In general, resonance involves energy oscillating between two modes, a familiar example being a mechanical pendulum in which energy oscillates between potential and kinetic forms. In a system at resonance, it is possible to have a large build-up of stored energy while having only a weak excitation to the system. The build-up occurs if the rate of energy injection into the system is greater than the rate of energy loss by the system.

The behavior of an isolated resonator can be described by two fundamental parameters, its resonant frequency ω_0 and its intrinsic loss rate, Γ . The ratio of these two parameters defines the quality factor or Q

of the resonator ($Q = \omega_0 / 2\Gamma$) a measure of how well it stores energy.

An example of an electromagnetic resonator is the circuit shown in Figure 4, containing an inductor, a capacitor and a resistor.

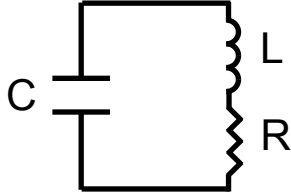


Figure 4: Example of a resonator.

In this circuit, energy oscillates at the resonant frequency between the inductor (energy stored in the magnetic field) and the capacitor (energy stored in the electric field) and is dissipated in the resistor. The resonant frequency and the quality factor for this resonator are

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad (1)$$

and

$$Q = \frac{\omega_0}{2\Gamma} = \sqrt{\frac{L}{C}} \frac{1}{R} = \frac{\omega_0 L}{R} \quad (2)$$

The expression for Q (2) shows that decreasing the loss in the circuit, i.e., reducing R , increases the quality factor of the system.

In highly-resonant wireless power transfer systems, the system resonators must be high- Q in order to efficiently transfer energy. High- Q electromagnetic resonators are typically made from conductors and

components with low absorptive (also sometimes referred to as ohmic, resistive, series resistive, etc.) losses and low radiative losses, and have relatively narrow resonant frequency widths. Also, the resonators may be designed to reduce their interactions with extraneous objects.

Benefits Afforded by a HR-WPT System

The high degree of scalability of power level and distance range in solutions based on highly resonant wireless power transfer enables a very diverse array of configurations. Applications range from very low power levels for wireless sensor and electronic devices needing less than 1 watt, to very high power levels for industrial systems and electric vehicles requiring in excess of 3 kilowatts.

There are four (4) major functional benefits of using highly resonant wireless power transfer systems as compared to systems based on traditional magnetic induction. The first is the flexibility in the relative orientations of the source and device during operation. This flexibility opens the application space as well as makes systems easier and more convenient to use. Second, a single source can be used to transfer energy to more than one device, even when the devices have different power requirements. For example, instead of having a separate charger for each mobile phone in your family, you can have a charging surface that handles all of them at once. Third, because of the ability to operate at lower magnetic coupling values, the sizes of the source and device resonators are not constrained to be similar. Finally, the distance range of efficient energy transfer

can be extended significantly through the use of resonant repeaters that enable energy to “hop” between them. These four functional benefits are illustrated in

Figure 5.

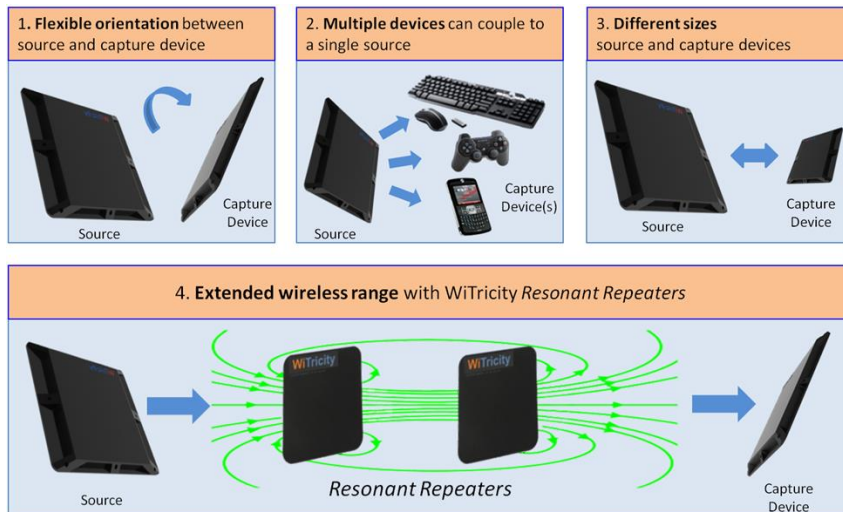


Figure 5: Schematic representation of the functional benefits of wireless energy transfer based on magnetic resonance.

Wireless energy transfer systems based on HR-WPT are being developed for numerous applications.

Operational Concepts

HR-WPT technology has the ability to enable a wide range of new underwater applications with power requirements ranging from several watts to several kilowatts. Many of the concepts for which there is a demand from the undersea community may be able to leverage previously developed WiTricity systems and technology to at least test the capabilities and provide proof-of-concept systems for HR-WPT subsea applications. One example that utilizes an existing WiTricity system in a subsea application is described in this

paper. The application being considered is that of recharging Autonomous Undersea Vehicles (AUVs) and UUVs while they are under water.

One can envision a system where an AUV or UUV moves alongside a larger vessel outfitted with a wireless power source and wirelessly receives power from that source, without any direct electrical or docking connections. The source vessel could range from a surface ship to a submarine, to an unmanned floating platform with a form of energy harvesting (such as solar panels) or power generation on-board.

Alternative solutions for providing power in these applications are unattractive because maneuvering, let alone holding the position of a UUV relative to another platform steady and in a precise position, can be difficult even in calm waters. While it is possible to have an UUV navigate into some form of mechanical dock or use an arm to capture and fixture the vehicle, the UUV would then have to actually receive its power through some form of wet-mate connector. These connectors are notoriously unreliable, both in terms of ensuring an adequate conductive path and generally having a very limited cycle life, even with frequent maintenance. An HR-WPT system could provide the necessary power in such applications without the need for docking, mating and other mechanical assemblies.

From a defense perspective, one could imagine a fleet of AUVs monitoring an

exclusion zone around a submarine or carrier group. These AUVs could survey an area, returning regularly to a “mothership” which they might follow alongside to recharge and transfer collected data.

A commercial application could see AUVs surveying large areas of the seafloor for exploration or monitoring of oil and gas infrastructure. The AUV could then return to either a surface vessel or a source mounted to a drilling rig or other underwater infrastructure.

In both of these potential applications, one can imagine UUV deployments of months or years without human intervention, or a need to surface to receive power, thus enabling new long-term missions previously thought unfeasible.

HR-WPT Modeling and Simulation

Since its founding, WiTricity has relied on modeling and simulation tools to design systems that can transfer power over distance safely and efficiently. The underlying models are continually improving and are quite accurate. Before building a prototype, WiTricity engineers model various resonator configurations and system designs and with great confidence predict the system efficiency and the strength of the electromagnetic fields around the system. This allows WiTricity to be confident a system design will be viable for an application, can be safely operated around humans and animals, and can be operated without interfering with other electronic systems in the environment.

Modeling Parameters

As an example for a subsea system, WiTricity engineers modeled how well the source and device resonators designed for terrestrial electric vehicle charging applications would perform under water. These particular resonators are offered as part of the WiT-3300 Development System. This system includes a source resonator in a 50 cm x 50 cm x 3.75 cm enclosure as shown in Figure 6. The device resonator, which in this concept would be mounted on the UUV, is housed in an enclosure that measures 24 cm x 27.8 cm x 2.2 cm. This development system has been designed to transfer 3.3 kilowatts to hybrid and full electric vehicles while meeting IEEE, FCC, and ICNIRP guidelines for human exposure to electric and magnetic fields.

In this modeling exercise, a value of 5 Siemens/meter was used to characterize the conductivity of sea water. For this example application, we assumed a source-device separation of 15 cm separation between resonators, and ran simulations to determine the efficiency of the system as the device resonator moved +/- 6 cm in the X direction and +/- 3 cm in the Y direction relative to the source. The center of the source resonator is defined as (0, 0) (See Figure 6.).

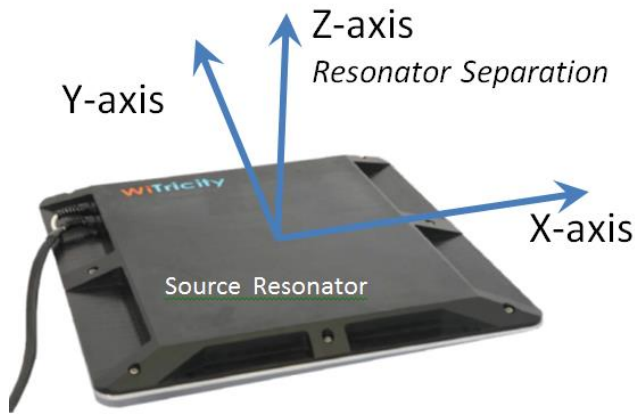


Figure 6: Coordinate System Used in System Modeling

System Performance Underwater

Over this operating range, the resulting simulation data show the wireless (resonator-to-resonator) efficiency ranges from 79.2% to 80.8% while transferring 3 kilowatts of power. The calculated data are shown in Figure 7. Note that because of the symmetry of the resonators, the data are only shown for +X and +Y offsets. The solid lines marked with numbers are the contours of constant efficiency for the number displayed (e.g. 80.8%, 80.6%, etc.) Note too, that the predicted efficiencies in Figure 7 are the wireless efficiencies which do not include losses due to any necessary stages of power conversion, RF amplification, and AC rectification.

Depending on the power source available to the system, the required voltage output on the device side, size constraints, and other design parameters, the efficiency of these additional electronic subsystems can vary

and may result in an additional efficiency loss of 5-10%

In order to demonstrate the capability of an HR-WPT system to transfer power through water, a proof-of-concept was constructed as shown in Figure 8.



Figure 7: Image of a HR-WPT system in operation transferring power through water

In this demonstration a HR-WPT source is connected to a source resonator on top of which is placed a plastic container filled with water. Placed on top of the water container is a capture resonator, connected to a halogen lamp. The separation between the two resonators is approximately 26cm.

System Improvements

The calculated efficiencies for the EV charging system operated under water are

about 15% lower than the predicted and measured performance in air, owing to the assumed conductivity of sea water. Improvement in system performance is possible through optimization of the system design. For example, the choice of operating frequency has a strong influence on system performance in the presence of conducting

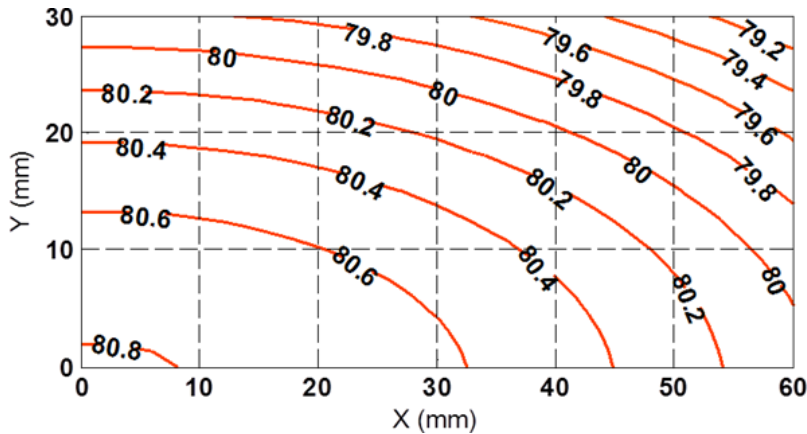


Figure 8: Calculated Efficiency Data at a Resonator Separation of 15cm

materials and in conducting media. The data shown here assumed one of the standard operating frequencies in the WiT-3300 system. A lower frequency will likely provide better performance. Also, custom resonators designed for application in this environment and for a specific operating range can provide efficiency improvements. Therefore, we believe wireless efficiencies can be improved over the results shown here with an application specific system design.

WiTricity is very interested in exploring novel underwater operational concepts and designing HR-WPT systems that may provide unprecedented capabilities to undersea products, capabilities, and missions.

Conclusion

We have modeled an existing WiTricity Highly Resonant Wireless Power Transfer system operating in an underwater environment and shown that several kilowatts of power may be transferred over an appreciable distance (15 cm) with a high level of efficiency (~80%). Unlike traditional inductive solutions or wet-mate connectors, HR-WPT systems do not need precision alignment or mechanical fixturing to transfer power efficiently. A fully integrated system would require minimal, if any, maintenance while providing a high-reliability solution over several years.

As underwater vehicles become increasingly autonomous and operational needs surpass what can be provided by a tethered Remotely Operated Vehicle (ROV) it is possible to imagine a wide variety of missions that could potentially be enabled by HR-WPT. The need to track and capture an UUV to recharge it could potentially be eliminated altogether over its service lifetime. At the same time, the cost of operating UUVs could fall dramatically, as specialized surface ships will no longer need to be dispatched on a regular basis to service and replenish a UUV's energy source.

HR-WPT has the potential to enable truly autonomous underwater vehicle operation in the deepest oil fields and even in the middle of the ocean.