Physics Education

Wireless power transfer experiments for a high-school physics lab

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PAPER

Phys. Educ. **54** (2019) 055016 (6pp)

iopscience.org/ped

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Abstract

The transfer of electrical energy without any electric leads or cables is not only a modern subject of research, but the technology has already found its way into our daily lives. Especially in consumer electronics a lot of applications are commercially available, mostly non-contact charging applications for toothbrushes, mobile phones, etc. On the other hand, the basic principle of this technology can be made understandable even for high-school students. For this purpose, we have developed a simple setup with which the elementary principle of wireless energy transfer can be shown. The setup design is user-friendly, straightforward, and easy to assemble for the students.

1. Introduction

In the late 19th century, Nikola Tesla had the vision of providing the world with electrical energy via wireless power transfer [1, 2]. Although his Tesla coil transformers turned out to be not suitable for this purpose, modern technologies have evolved that are not too far off this early vision. In 2007, Kurs *et al* presented the idea of coupled resonances [3]: there, power is transmitted via a magnetic field using two coils where each of them is an integrated element of a resonant circuit on the transmitter and receiver side, respectively. Power transfer is particularly efficient if the driving frequency of the circuits is matched to their intrinsic resonance frequency. Nowadays, this method is used in various modern applications, such as inductive charging for consumer electronics [4]. Since the students experience this technology in their everyday life and as the physics on which it is based is not really hard to understand, we developed an educational experiment to teach high-school students the principles of modern wireless power transfer.

2. Basic principle of wireless power transfer with resonant circuits

Transmitting electrical power wirelessly is carried out by a magnetic field that is generated by a transmitter coil and received by a receiver coil. Figure 1 shows the circuit and the components that are needed. The transmitter coil L_T and a capacitor C form a resonant circuit that is driven by an AC voltage U from a frequency generator at its resonance frequency (figure 1, left circuit). The additional resistor R can be very small and is used to prevent short-circuiting since there is no other electrical resistance in the circuit. The receiver circuit (figure 1, right circuit), consisting of the receiver coil L_R, the capacitor C and a load resistor R_L, must have the same resonance frequency as the transmitter circuit. This match in resonance frequencies allows optimal coupling of the magnetic field and, therefore, the highest efficiency of the energy transfer can be achieved. The simplest way to implement the resonance condition is to use the same capacities and inductivities for the transmitter and receiver capacitors and coils, respectively.

This is indeed what we will do in the following. It can be added that differences in the resonance frequency are basically not harmful, however, the power transfer is simply less efficient off resonance and hence more difficult to demonstrate in these basic experiments.

For teaching at high-schools the influence of the resistors and leads can be neglected. For this resonant inductive coupling technique, frequencies in a range from kHz to GHz are usually used. To find out more about the frequency dependency of this power transmission system and to show the importance of the resonance condition, we performed the following experiments.

3. Experimental setup—analysing the resonance behaviour

In a first quantitative experiment it can be worked out how the driving frequency influences the efficiency of the power transfer and how the coil parameters can be used to tune the frequency at which the most efficient power transfer occurs. We used the circuits as shown in figure 1, with capacitor $C = 0.22\ \mu$F, resistor $R = 3.3\Omega$ and the inductivities $L_R = L_T$ that are unknown in general but subject to modifications. Our frequency generator was a PeakTech 4115 with an 8W power amplifier. It should be noted that a power amplifier is needed, since non-amplified generators do not deliver enough power to actually drive lamps or other electric loads. We used various pairs of identical coils: three homemade pairs and one commercial pair for inductive chargers (Würth Elektronik WE-WPCC). Table 1 shows the parameters of the used coil pairs, with N being the number of turns and r the coil radius.

To obtain the order of magnitude of the resonance frequency f_0 of our circuits, we can apply the well-known relation

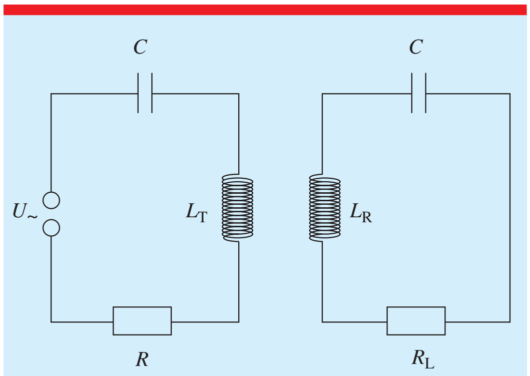

Figure 1. Resonant circuits for wireless power transfer. Left: transmitter circuit, right: receiver circuit.

$$f_0 = \frac{1}{2\pi\sqrt{LC}}. \tag{1}$$

It should be mentioned that this is only a rough approximation to estimate the resonance frequency, since there is also a mutual inductance between the coils. However, considering this in detail would go beyond the scope of any high school curriculum. So we used this relation to estimate the resonance frequencies of each single circuit. This can be done experimentally: The complex impedance Z of an LCR circuit like the two circuits in figure 1 is given by

$$Z = R + \mathrm{i}\left(\omega L - \frac{1}{\omega C}\right), \tag{2}$$

with the ohmic resistance R, the inductance L, the capacity C, and the excitation frequency $\omega = 2\pi f$. At the resonance frequency, the imaginary part of this expression becomes zero and only the ohmic resistance remains, so that we obtain $\omega_0 = \frac{1}{\sqrt{LC}}$, or, as in equation (1), $f_0 = \frac{1}{2\pi\sqrt{LC}}$. Practically, this means: If the LCR circuit is excited at the resonance frequency f_0, the voltage across the coil and the capacitor becomes zero, since their reactances cancel each other out. By finding out when this voltage becomes zero while varying the excitation frequency a rough value of the resonance frequency can be determined. As there are additional resistances, reactances and losses in the leads and components, this value is not very accurate but a good approximation.

After we have found out the approximate values of the resonance frequencies of each individual circuit, we wanted to find the resonance frequencies of each transfer system, consisting of both a transmitter and receiver circuit. Our final goal is to find the optimal frequencies for the energy transfer. For each coil pair, we varied the frequency of the generator close to the approximate value and measured the efficiency of the power transfer. For all experiments we used a coil distance of 2 cm. Then, we measured the transmitter circuit voltage U_T and current I_T and the receiver circuit voltage U_R and current I_R. Thus, we obtain for the input power P_{in} and the output power P_{out}

$$P_{in} = \frac{U_T}{\sqrt{2}} \cdot I_T, \tag{3}$$

$$P_{out} = \frac{U_R}{\sqrt{2}} \cdot I_R. \tag{4}$$

Please note: $U_{T,R}$ were measured with an oscilloscope and are the *peak values* of the voltage, whereas $I_{T,R}$ are the *effective values* of the current, measured with an ammeter. That's why the factor $1/\sqrt{2}$ appears only once in this expression.

The efficiency is defined as

$$\eta = \frac{P_{out}}{P_{in}}. \tag{5}$$

Figure 2 shows the efficiency of the four considered coil pairs as a function of the excitation frequency. First of all, it can be observed that the coils with larger radius exhibit lower resonance frequencies than the coils with a smaller radius, while having the same number of turns. Coil 3 has a resonance frequency of ca. 73 kHz while the smaller Coil 1 has about 126 kHz (both with five turns). The same can be observed for Coil 2 (15 turns) and Coil 4 (15 turns but smaller radius), with resonance frequencies at 53 kHz and 90 kHz, respectively. It can be shown that in short coils, as we use them here, the inductance increases with the coil radius and with the number of turns [5]. With equation (1) it becomes clear that the resonance frequency decreases with increasing coil inductance. When comparing the equally sized Coils 1 and 2 with five and 15 turns, it can be observed that Coil 1 has a higher resonance frequency than Coil 2, due to its lower inductance.

Students can also see that, while having the same number of turns, the coils with a larger radius show a much higher efficiency at resonance—ca. 28% with Coil 3 compared to ca. 9% with Coil 1, both having five turns. The same can be found for the systems with 15 turns: With the larger Coil 2 we obtain an efficiency of ca. 37%, with Coil 4 only about 7%. We can also observe that the number of turns increases the efficiency as well. Comparing the system with the coils of equal size, Coil 1 and Coil 2, we find a much higher efficiency for Coil 2 (15 turns) than for Coil 1 (five turns).

Table 1. Parameters of the used coil pairs.

Coil pair	N	r (cm)
Coil 1	5	5.5
Coil 2	15	5.5
Coil 3	5	15.0
Coil 4	15	2.5

An intuitive way of explaining these findings to the students could be that a larger number of turns and a larger coil radius improve the coupling of the magnetic field in both coils, i.e. a higher amount of magnetic flux generated by the transmitter coil passes through the receiver coil and more energy can be transmitted. Since the efficiencies of such systems strongly depend on the detailed coil geometries it would be too extensive to discuss these relations within the scope of this paper, so we suggest the interested reader to study additional literature [6, 7].

On this very basic level, these experiments can be performed by students. They can learn how the coil parameters influence the resonance frequency of a system and how they affect its efficiency. It is interesting that larger coils with a higher number of turns are obviously favourable for high efficiencies. However, for charging consumer electronics such as mobile phones or electric toothbrushes small coils must be used since the customer would rather favour small devices. This shows that it is a demanding task to achieve acceptable efficiencies for everyday applications [8].

4. Wireless power transfer setup with applications

Now we want to use our setup to actually drive some applications with it. The setup is shown in figure 3. Except from the coils it is identical to the setup just considered: G denotes the frequency generator. For better handling, we now use a commercial set of two identical coils provided by 3B Scientific, with $N = 100$ turns, coil

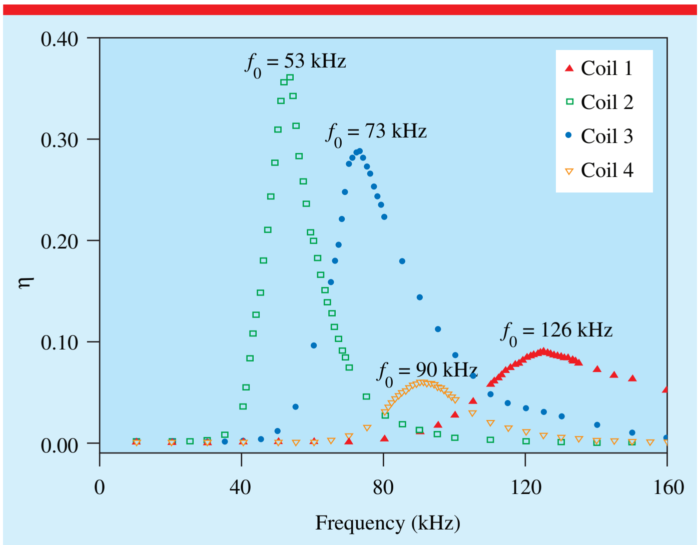

Figure 2. Transmission efficiency depending on the excitation frequency.

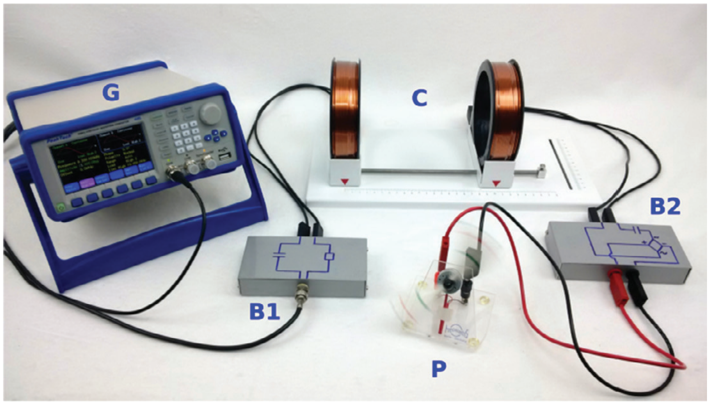

Figure 3. Setup for WPT application experiments. G: frequency generator, C: board with coils, B1 and B2: transmitter and receiver circuit boxes, P: toy propeller.

radius $r = 6.25$ cm and inductance $L = 1.8$ mH (each coil). The coils are mounted on a board (C) such that one of the coils can be displaced parallel to the other, so that their distance can be adjusted from 0 cm to 24 cm. The transmitter circuit is identical to the transmitter circuit in figure 1. The receiver circuit is additionally equipped with a rectifier at the output. Its integration is necessary for our applications that require direct current (see figure 4).

As we like to focus on the application in this experiment, we mounted the electronics (capacitors, resistors, rectifier) in small boxes (B1 and B2) on which the circuit is drawn so that the students know what is inside and can connect the coils and the applications on their own. As load/application we use a small toy propeller (P), little light bulbs (6 V), or LED arrays (not shown in the image). It is much more motivating for students to drive little gadgets than to only measure the voltage or current output on the receiver side to see that energy was transferred. So, the load resistor in the circuit is defined by the connected gadget. Since these experiments are motivational add-ons we have not investigated possible changes in the circuit performance caused by the different loads. However, qualitatively, all experiments worked well in practice.

Firstly, students can calculate the approximate resonance frequency of the setup by

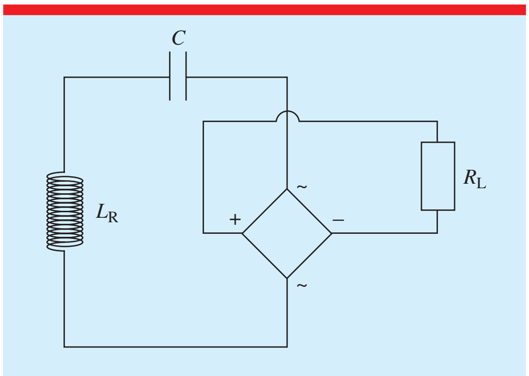

Figure 4. Receiver circuit with additional rectifier.

applying equation (1), obtaining $f_0 \approx 8\,\text{kHz}$. Then, they can find the exact value as described above: By varying the frequency in small steps and observing the rotation velocity of their propeller at a defined coil distance, they can find out that the highest velocity and, therefore, the resonance frequency is reached at $f_0 = 8.3\,\text{kHz}$. The exact value, of course, depends on the electrical details of the circuit that are hard to predict.

After knowing the resonance frequency, students can vary the coil distance of the transmitter and the receiver and study how this affects the brightness of the LEDs/lamps or the rotation velocity of the propeller. They can also vary the input power from the frequency generator. Having more experienced students, the experiments can be performed quantitatively by measuring all voltages and currents while observing the LED's brightness or the propeller's velocity. Younger students can just qualitatively study all the effects and dependencies by observing the behaviour of the gadgets on the output side. They find it fascinating that the propeller can be driven even when the coils are set to the maximum distance of 24 cm.

Conclusion

We have designed a simple experimental setup with which high-school students can learn the working principle of modern wireless power transfer. It is possible to perform experiments with students on different levels of knowledge and skills. Our aim is to make that up-to-date technology and its advantages and disadvantages understandable for high-school students. We have found that students are fascinated that they can almost 'magically' power lights and gadgets with a power source that is not connected in any way directly to them, although they already knew about applications such as wireless charging stations.

Acknowledgement

We acknowledge support by the KIT-Publication Fund of the Karlsruhe Institute of Technology.

Received 15 April 2019, in final form 15 May 2019
Accepted for publication 24 June 2019
https://doi.org/10.1088/1361-6552/ab2c2c

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Antje Bergmann received her Ph.D. in 2006 at the University of Regensburg in the research field of polymer physics. In October 2006 she became a permanent researcher at the physics department at the Karlsruhe Institute of Technology. Being the head of various physics lab courses and a high school students' lab she started to focus her research interests on the development of new lab course experiments and setups for both high school lab experiments and advanced undergraduate university lab courses.

Enrico Dürr is a newly appointed grammar school teacher for physics and mathematics. He graduated at the Karlsruhe Institute of Technology and wrote his thesis for his final exam on lab experiments for high school students with the focus on wireless power transfer.

Carsten Rockstuhl received the Ph.D. degree from the University of Neuchatel, Switzerland, in 2004. After a PostDoc period at AIST in Tsukuba, Japan, he has been since 2005 with the Friedrich Schiller University Jena, Germany. In 2013, he was appointed full professor at the Karlsruhe Institute of Technology, Karlsruhe, Germany. There, he is heading groups at the Institute of Theoretical Solid State Physics and the Institute of Nanotechnology.His research interests cover many aspects in the context of theoretical and computational nanooptics. Among others, he works on nanostructured photonic materials, plasmonics, scattering theory, integrated photonics, quantum optics, and nonlinear photonics.