Wireless Solar Energy to Homes: A Magnetic Resonance Approach

Steven A. Hackworth, Xiaoyu Liu, Chengliu Li, and Mingui Sun

Department of Electrical & Computer Engineering, University of Pittsburgh, Pittsburgh, PA 15261 USA

stevenahackworth@gmail.com, liu-xy@hotmail.com, chengliu.li@gmail.com, drsun@pitt.edu

***Abstract*—We describe a novel method for wireless transmission of solar power to the interiors of homes and buildings. This method is based on wireless electricity (witricity), a new technology developed recently in the field of physics. Two thin film witricity resonators are placed behind the solar panel and on the inside of the building, with no cable connection between the two. High-efficiency energy transfer is achieved across a wall or roof in the form of magnetic resonance at approximately 7 MHz. Significant savings in installation cost can potentially be achieved using this wireless energy transfer method, encouraging adoption of a "green" source of energy.**

***Index Terms*—Magnetic Resonance, Solar Energy, Wireless Transmission, Witricity.**

I. INTRODUCTION

IN RECENT years, there has been an increasing trend of using renewable energy, including installing solar panels in residential homes, propelled by public concerns about the environment and favorable federal tax incentives. Currently, the cost of solar panels has decreased substantially. For example, the low-end price of 10-15 Watt panels is at the level of $100 and still decreasing. However, considerable structural modification and installation, including the creation of a through hole, are required for connecting a cable to the house interior and properly grounding the panel to prevent danger from lightning strikes. The associated cost is high, often comparable to the purchase cost of the panel or even higher.

We present a method to transmit energy from solar panels through structural walls or roofs using a newly developed wireless energy transfer technology called witricity. A comparison between existing solar installations and the proposed wireless method is shown in Fig. 1. Our system utilizes magnetic fields below 10 MHz which are essentially unaffected by commonly used home construction material. Because of the wireless connection, most structural modifications to the house can be eliminated, installation costs can be reduced, and solar panels can be moved or replaced easily. Since magnetic fields have less biological effects on the human body than electromagnetic fields at higher frequencies, the witricity approach is safer than a traditional radio-frequency approach at comparable power levels.

In this work, we make the initial attempt to use wireless energy transfer for solar panels. The primary goal of this work is to demonstrate that this energy transfer is technically feasible. Therefore, we will focus only on the applicable theory and the witricity resonator part of the system. Other factors of the system, such as the power generation characteristics of the solar panel and the efficiency of power electronics will not be considered in this paper.

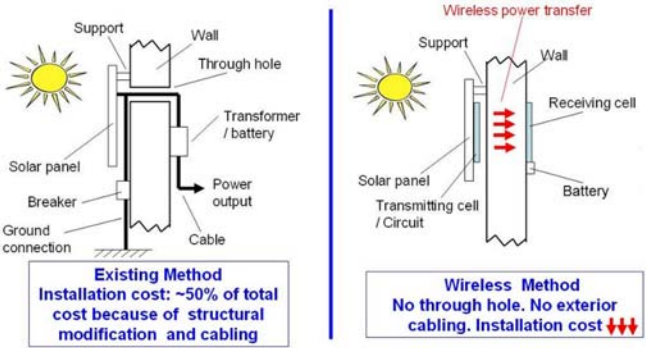

Fig. 1. Comparison of existing and wireless solar panel systems.

II. WITRICITY THEORY

Witricity is a recent development in physics that allows efficient energy transfer over a distance without wires (Kurs et al. 2007; Karalis et al. 2008). Unlike traditional methods using electromagnetic waves radiated throughout the entire surrounding space, witricity transfers power along a virtual path between the source and the target which resonate at the same frequency. Off-resonant objects in the surrounding area interact only weakly with the resonant system. As a result, the efficiency of energy transfer is much higher. Researchers at MIT transferred 60W of power over seven feet with 40% efficiency (Kurs et al. 2007). A different design by Intel recently reached 75% efficiency over three feet (Robertson 2008).

Witricity systems can be designed to use different types of fields. In our particular application the magnetic field is utilized. Our system consists of four components: two high-Q resonators (a source resonator and a device resonator) which exchange energy back and forth, a driving loop which is powered externally, and an output coil which captures energy for the load (Fig. 2). Energy is added to the resonant system via magnetic coupling between the driving loop and the source resonator, and lost from the system via inherent component losses, radiated energy, and power dissipation in the load.

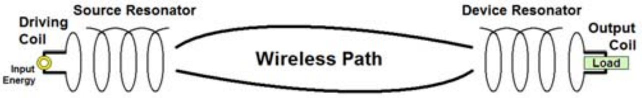

Fig. 2. General witricity system design.

The energy in the witricity system can be modeled with a pair of differential equations by using coupled mode theory (Kurs et al. 2007; Karalis et al. 2008; Zhang et al. 2009b; Haus 1984):

$$\frac{da_1(t)}{dt} = (j\omega_1 - \Gamma_1)a_1(t) + j\kappa a_2(t) + f(t) \qquad (1)$$

$$\frac{da_2(t)}{dt} = (j\omega_2 - \Gamma_2)a_2(t) + j\kappa a_1(t) \quad . \qquad (2)$$

$a_i(t)$ is defined such that $|a_i(t)|^2$ is the energy over time in resonator i. ω_i and Γ_i are the resonant frequency and loss factor, respectively, associated with resonator i, κ is the coupling factor between resonators, j is the imaginary number $\sqrt{-1}$, and $f(t)$ is the input energy from the driving loop.

To calculate $a_i(t)$, we use the Laplace transform and obtain

$$L\{a_1(t)\} = \frac{\left(L\{f(t)\} + a_1(0)\right)\left(s - j\omega_2 + \Gamma_2\right) + j\kappa a_2(0)}{\left(s - j\omega_1 + \Gamma_1\right)\left(s - j\omega_2 + \Gamma_2\right) + \kappa^2} \qquad (3)$$

$$L\{a_2(t)\} = \frac{j\kappa\left(L\{f(t)\} + a_1(0)\right) + \left(s - j\omega_1 + \Gamma_1\right)a_2(0)}{\left(s - j\omega_1 + \Gamma_1\right)\left(s - j\omega_2 + \Gamma_2\right) + \kappa^2} \quad . \qquad (4)$$

Let us examine how the energy in the system changes over time. Assume $f(t) = 0$ (no input energy) and, at arbitrary $t = 0$, the total energy, A, is in resonator 1 and no energy is in resonator 2, i.e. $a_1(0) = \sqrt{A}$ and $a_2(0) = 0$. This gives

$$L\{a_1(t)\} = \frac{\left(s - j\omega_2 + \Gamma_2\right)\sqrt{A}}{\left(s - j\omega_1 + \Gamma_1\right)\left(s - j\omega_2 + \Gamma_2\right) + \kappa^2} \qquad (5)$$

$$L\{a_2(t)\} = \frac{j\kappa\sqrt{A}}{\left(s - j\omega_1 + \Gamma_1\right)\left(s - j\omega_2 + \Gamma_2\right) + \kappa^2} \qquad (6)$$

from which we can compute the time domain solutions

$$a_1(t) = \sqrt{A}e^{-\frac{(\Gamma_1+\Gamma_2)}{2}t}e^{j\frac{(\omega_1+\omega_2)}{2}t}\left[\cos\left(\frac{t}{2}\sqrt{((\omega_1-\omega_2)-j(\Gamma_2-\Gamma_1))^2+4\kappa^2}\right)+\right.$$
$$\left.\frac{(\Gamma_2-\Gamma_1)-j(\omega_1-\omega_2)}{\sqrt{((\omega_1-\omega_2)-j(\Gamma_2-\Gamma_1))^2+4\kappa^2}}\sin\left(\frac{t}{2}\sqrt{((\omega_1-\omega_2)-j(\Gamma_2-\Gamma_1))^2+4\kappa^2}\right)\right] \qquad (7)$$

$$a_2(t) = \sqrt{A}e^{-\frac{(\Gamma_1+\Gamma_2)}{2}t}e^{j\frac{(\omega_1+\omega_2)}{2}t}\left[\frac{j2\kappa}{\sqrt{((\omega_1-\omega_2)-j(\Gamma_2-\Gamma_1))^2+4\kappa^2}}\times\right.$$
$$\left.\sin\left(\frac{t}{2}\sqrt{((\omega_1-\omega_2)-j(\Gamma_2-\Gamma_1))^2+4\kappa^2}\right)\right] \qquad (8)$$

Equations (7) and (8), being very general, are overly complex for our application. Practically, resonators in a witricity system are designed with minimal difference between their resonant frequencies. Also, if the resonators are identical in structure and we neglect the effect of the load in our examination, their loss factors will be equal. Thus we assume $\omega_1 = \omega_2 = \omega$ and $\Gamma_1 = \Gamma_2 = \Gamma$ and simplify (7) and (8) to the following:

$$a_1(t) = \sqrt{A}e^{-\Gamma t}e^{j\omega t}\cos(\kappa t) \qquad (9)$$

$$a_2(t) = \sqrt{A}e^{-\Gamma t}e^{j\omega t}j\sin(\kappa t) \qquad (10)$$

If the ratio between the coupling and loss factors is high enough, practically $\kappa/\Gamma >> 1$, energy can be efficiently exchanged between resonators at a high rate. This phenomenon differs significantly from the traditional magnetic induction and radio transmission systems where the energy flow is essentially unidirectional (from the transmitter to the receiver). From (7)-(10), we can interpret that energy in a witricity system oscillates between each resonator. If we examine the total system energy,

$$E_T = E_1 + E_2 = |a_1(t)|^2 + |a_2(t)|^2 = Ae^{-(\Gamma_1+\Gamma_2)t} \qquad (11)$$

we see that it decays exponentially according to the loss rates. As a result, energy can efficiently be kept in a low-loss resonant system until output to a load via magnetic coupling. Input energy from the driving loop, $f(t)$, must simply be enough to compensate the system and load losses in order to sustain the resonant oscillations. Additionally, both the literature and our own experiments have indicated that the source and device resonators do not have to be in precise alignment (Kurs et al. 2007; Zhang et al. 2009a), which facilitates the use of witricity in many applications.

III. METHODS

A. Planar Coil Design

Because of the importance of the resonator parameters, we give much consideration to the design of the coils for the witricity system. The resonator design described in (Kurs et al. 2007) is an unconnected large coil having a shape unfavorable for the solar application. Here we present a thin-film design for both the source and device resonators, suitable for use with a solar panel and flat receiving device. Our design consists of two patterned layers of 0.066 mm copper foil tape conductor on either side of one layer of 0.255 mm clear polycarbonate film used as a resonator base and insulator. As illustrated in Fig. 3(a), the two conductor layers provide a coil and several local capacitors across the insulator layer, forming a complex LC oscillator. The resonant frequencies of the resonators are tuned by adjusting the length of the coils and the number and lengths of the capacitive strips on the coils as well. Ours are tuned to 6.54 MHz, close to one of the official industrial, scientific, and medical (ISM) frequencies (6.78 MHz). Fig. 3(b) shows one of the coils after completion with a side length of 32 cm. This fits the shorter dimension of a 10-Watt solar panel, roughly 35 cm. A driving loop was constructed from insulated 12-gauge copper wire. The output coil was built in a spiral fashion from ¼-inch copper pipe, seen in Fig. 4(c).

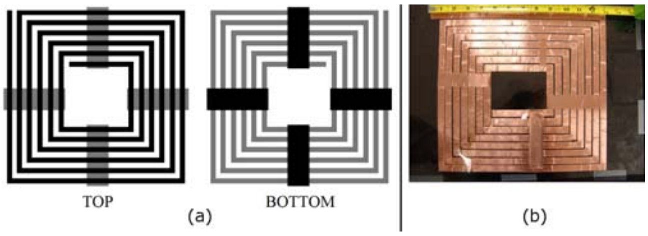

Fig. 3. (a) Resonant coil structure. The thin polycarbonate substrate (not shown) lies between the copper foil layers, the closest copper layer being darker in color. (b) "Bottom" view of actual constructed resonator.

B. *Experimental Setup*

The wireless transfer system was set up as shown in Fig. 4. A brick wall was erected between the source and device resonant coils. The driving loop was powered on the source coil side by an amplifier with a simulated solar panel power input and driven by a sinusoidal signal from a function generator. The load coil was positioned near the resonant device coil to draw energy from it via magnetic coupling. Because currently we cannot accurately determine the effects of this electromagnetic exposure on the human body next to the experimental device, we intentionally use very low RF power (less than one Watt) to operate the witricity system. Calculated efficiency results at higher energy levels will be the same since the system is theoretically linear.

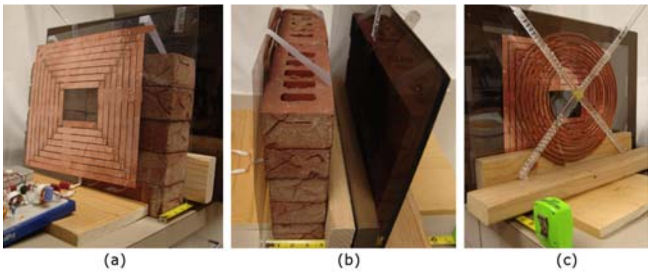

Fig. 4. (a) Transmitting side of the system with amplifier and resonant coil. (b) Constructed wall between resonant coils. (c) Receiving side of the system, showing the square resonant coil and spiral load coil.

C. *Power Transfer Efficiency*

The power transfer efficiency of the setup is calculated by dividing the power received on the load coil side, P_L, with the power transmitted at the driving loop, P_T. The load resistance was chosen to maximize power transfer to the load, a 1.8kΩ resistor for these experiments. The sinusoidal voltage amplitude, V_L, across this resistor, R_L, is measured to calculate the received power in the load by the equation $P_L = V_L^2/(2R_L)$. On the transmitting side, P_T is measured as the power going to the driving loop. Fig. 5(a) illustrates the setup used in this measurement. A resistor R (56Ω in this case) is put in series with the driving loop. The voltage V_R is measured across R in order to determine the amplitude of the sinusoidal current going into the driving loop ($I_R = V_R/R$). The voltage across the driving loop, V_C, and the total voltage across both the resistor and driving loop, V_T, are also measured in order to calculate the phase, γ, between the voltage and current of the driving loop, using the law of cosines (see Fig. 5(b)). The total power going to the driving loop is calculated as $P_T = V_C * I_R * \cos(\gamma)/2$.

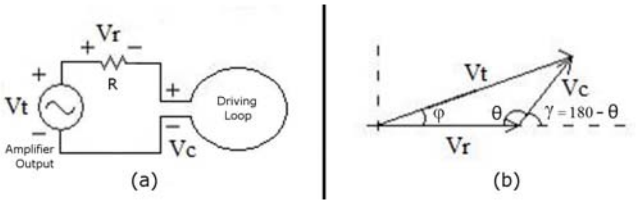

Fig. 5. (a) Schematic of P_T measurement setup. (b) Voltage relationships to calculate the phase angle between the driving loop's voltage and current.

IV. EXPERIMENTAL RESULTS

Fig. 6 shows the measured power transfer efficiency of the witricity system at various distances. As can be seen, the efficiency decreases as a function of resonant coil separation, with the highest efficiency being 52% at the smallest distance (5.75 inches), and decreasing to 4% at a distance of fourteen inches. With most exterior walls ranging in thickness from four to nine inches, this first generation witricity system would provide for an energy transfer efficiency of ~30% to more than 52% in the solar panel application. The energy transfer performance was essentially unchanged when other objects such as plastics, plasters, water, and even a small number of metal screws and nails, were placed between the two resonators. Perfect alignment of the resonators is also not required to maintain efficiency, as opposed to standard inductive coupling in which alignment is an essential requirement.

Fig. 6. Power transfer efficiency is measured as the ratio of power delivered to the load to the power delivered to the driving loop, P_L/P_T. The highest efficiency for this system is

51.9% at 5.75 in.; the lowest is 4.0% at 14 in.

In practice, it is favorable to use the backside of the solar panel as the base of the source resonant coil. We performed an additional experiment in which the coil was attached directly to the back of a solar panel. The panel consists of a plastic substrate material with photovoltaic cells on one side. The cells are connected with a network of metal strips to collect current from individual cells. We again used a power supply to simulate the solar panel due to the lack of indoor sun.

Although we utilized exactly the same setup as that in the previous experiment, except for the presence of the solar panel, we observed a significant reduction in energy transfer efficiency. The highest measured efficiency at the closest possible distance (5.75 inches for this setup) was 33%. Although the efficiency suffered, of note is the interesting fact that the actual transmitted power, P_T, decreased tremendously, to a quarter of that without the solar panel present.

V. DISCUSSION

Witricity technology, though still in its infant stages, promises to be a feasible means for transferring significant levels of power from exterior solar panels to receiving devices within houses or buildings. In order for widespread adoption of the technology as a standard cost-saving solar installation alternative, the benefits of quick and easy installation must outweigh the loss of energy inherent with the wireless transfer. We have shown that planar, thin-film coils make suitable resonators for the system, achieving efficiencies of greater than 50% across reasonable distances. Considering that a well-designed laboratory witricity system by Intel has achieved a 75% efficiency over three feet (Robertson 2008), further improvements to the system setup and resonator design should increase the efficiency to a significantly higher level.

Due to the analytical difficulty of the complex resonators, no optimization beyond frequency tuning and form fitting to the application can easily be performed. Further optimizations include changing the resonator structure, coil pattern, and size to shape the magnetic field for maximum coupling across the intended distance. We have begun initial finite element simulations to conduct structural design and functional optimization, though further effort is necessary in this pursuit.

One phenomenon noticed in the experimental measurements was the change of the load seen by the amplifier. At closer distances, the phase, γ, between the voltage and current of the driving loop was relatively small, around thirty degrees. As the resonator separation increased, the phase angle increased as well, signifying the load was becoming more inductive. Because of the lesser coupling between transmitter and receiver at longer distances, the resistive load was increasingly disconnected. Judging from this phenomenon, the high Q values and oscillations of the resonators serve to create a strong magnetic flux channel between the coils. This strong flux linkage, similar to that in a standard transformer, reflects the load impedance to the transmitting side. As the coils get farther apart, the flux linkage becomes weaker, and thus the amplifier load appears to be simply an inductive loop and coil. Because of the relatively short distance between resonators in the solar panel application, strong flux linkage and subsequent coupling of the output load to the transmitting circuitry will be guaranteed.

Regarding the drop in efficiency with the inclusion of the solar panel in close proximity to the source resonator, one reason could be the energy loss due to the loop current through the metal strips. However, these strips do not form loops by themselves, instead being connected through the highly resistive solar cells. The 75% decrease in transmitted power also suggests a different mechanism: detuning of the resonant system due to the conductive strips. Without matched resonant frequencies on transmitter and receiver sides, the flux channel between resonators is not optimally created and thus the resistive load does not get coupled to the driving loop. Future studies will examine this detuning effect and even include the phenomenon in the official design and tuning of the resonator coils, allowing the source resonator to be attached to the backside of the solar panel.

Adoption of the technology also depends on the safety characteristics of the system. We believe the witricity technology, especially in this application, to be safe for a number of reasons: 1) energy is transmitted primarily in the form of a magnetic field, which has a smaller effect on biological tissue than an electric or electromagnetic field since induced eddy currents by magnetic fields in tissue produce smaller heating effects when compared to other fields, 2) the frequency (ones to tens of megahertz) is well above the range which causes nerve or muscle stimulation, and 3) most solar panel installation sites are far from common living areas in the rest of the house, making exposure minimal to begin with.

We point out that this work represents only the first attempt at using wireless energy transfer for solar power. Our primary goal is to show such transfer is technically feasible with the use of a practical resonator design. Although theoretical analyses and experimental data suggest a positive outcome, our system so far is primitive, and solar panel power output as a driving source, as well as electronics efficiency, were not considered. Substantial future engineering efforts will be required to produce feasible systems.

VI. CONCLUSION

A wireless energy transfer system based on witricity technology has been proposed to reduce the cost of solar panel installation and encourage its adoption. Experiments on an initial system utilizing appropriate flat thin-film resonators display power transfer efficiencies higher than fifty percent. Future research promises to increase to establish witricity as a cost-efficient solar installation solution.

VII. ACKNOWLEDGMENT

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VIII. REFERENCES

Haus, H. A. (1984) *Waves and fields in optoelectronics*. Englewood Cliffs: Prentice hall, pp. 197-234.

Karalis, A., Joannopoulos, J.D., and Soljacic, M. (2008) Efficient wireless non-radiative mid-range energy transfer. *Annals of Physics*, 323, pp. 34-48.

Kurs, A., Karalis, A., Moffatt, R., Joannopoulos, J. D., Fisher, P., and Soljacic, M. (2007) Wireless power transfer via strongly coupled magnetic resonances. *Science*, 317, pp. 83-86.

Robertson, J. (2008) How to power up without plugging in. Available from: http://www.msnbc.msn.com/id/26349363/ [Accessed on 28 Oct 2009].

Zhang, F., Liu, X., Hackworth, S. A., Sclabassi, R. J., and Sun, M. (2009a) In Vitro and In Vivo Studies on Wireless Powering of Medical Sensors and Implantable Devices. *Proceedings of the Fourth Annual IEEE-NIH Life Science Systems and Application*, 9-10 Apr, Bethesda, Maryland, USA.

Zhang, F., Liu, X., Hackworth, S. A., Micke, M. H., Sclabassi, R. J., and Sun, M. (2009b) Wireless power transfer in the home environment via strongly coupled magnetic resonance. *Proceedings of the 2009 International Symposium On Digital Life Technologies: Human-Centric Smart Living Technology,* 28-30 May, Tainan, Taiwan.

Steven Hackworth received the B.S., M.S., and Ph.D. degrees in electrical engineering from the University of Pittsburgh, Pittsburgh, PA, in 2004, 2005, and 2010, respectively. He currently works as a Research Associate in the department of neurosurgery at the University of Pittsburgh. Research interests include energy transfer technologies, sensor applications, and embedded system design.

Xiaoyu Liu received the B.S. and M.S. degrees in electrical engineering from Tsinghua University, Beijing, China, in 2005 and 2007, respectively. He is currently a Ph.D. student in electrical engineering at the University of Pittsburgh, Pittsburgh, PA. His research focuses on wireless energy transfer and energy harvesting circuit design for RFID systems.

Chengliu Li received his B.S. degree in 2005 in electrical automation from Yanshang University in Qinhuangdao, China, and his M.S. degree in electrical engineering in 2008 from Beijing Jiaotong University in Beijing, China. He is now a graduate student in electrical engineering at the University of Pittsburgh. Mr. Li's current research interests include fuzzy logic application and wireless power transmission.

Mingui Sun received the B.S. degree from the Shenyang Chemical Engineering Institute, Shenyang, China, in 1982, and the M.S. and Ph.D. degrees in electrical engineering from the University of Pittsburgh, Pittsburgh, PA, in 1986 and 1989, respectively. In 1991, he joined the faculty at the University of Pittsburgh, where he is currently a Professor in neurosurgery, electrical and computer engineering, and bioengineering. He has authored or coauthored more than 250 papers. His current research interests include advanced biomedical electronic devices, biomedical signal and image processing, biomedical instruments, implantable devices, EEG and MEG, and the inverse problem of neurophysiological signals.