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Araştırma Makalesi / Research Article

Research and Analysis of Wireless Power Transfer Technology Based on Sustainable Energy

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Keywords
Wireless power transfer; Inductive power transfer; Solar energy; Wind energy

Abstract

Wireless power transfer (WPT) has been a topic of interest, especially in sustainable energy-based applications in recent years. The reason for this is the increase in the demand for energy originating from both social and political issues. Providing robust and flexible solutions without the need for wires, WPT technology in sustainable energy applications are thoroughly examined in this paper. The applications are categorized into two types as solar energy and wind energy. Herein, the inductive and microwave wireless charging technologies become prominent among other wireless charging technologies. The merits and demerits of WPT technology in sustainable energy applications are also evaluated in this paper. Besides, the design and analysis of inductive power transfer as promising technology are presented in solar energy applications. This paper is also expected to shed light on researchers who are interested in WPT technology based on sustainable energy.

Sürdürülebilir Enerjiye Dayalı Kablosuz Güç Transferi Teknolojisinin Araştırma ve Analizi

Anahtar kelimeler
Kablosuz güç transferi; Endüktif güç transferi; Güneş enerjisi; Rüzgar enerjisi

Öz

Kablosuz güç aktarımı (WPT), özellikle son yıllarda sürdürülebilir enerji tabanlı uygulamalarda ilgi çeken bir konu olmuştur. Bunun nedeni hem sosyal hem de politik nedenlerden kaynaklanan enerji talebindeki artıştır. Kablolara ihtiyaç duymadan sağlam ve esnek çözümler sunan WPT teknolojisi, bu makale kapsamında sürdürülebilir enerji uygulamalarında kapsamlı bir şekilde incelenmektedir. Uygulamalar güneş enerjisi ve rüzgâr enerjisi olmak üzere ikiye ayrılmaktadır. Burada, diğer kablosuz şarj teknolojileri arasında endüktif ve mikrodalga kablosuz şarj teknolojileri öne çıkmaktadır. WPT teknolojisinin sürdürülebilir enerji uygulamalarında yararları ve zararları da bu makalede değerlendirilmektedir. Ayrıca, güneş enerjisi uygulamalarında gelecek vaat eden bir teknoloji olarak endüktif güç transferinin tasarımı ve analizi sunulmaktadır. Bu makalenin aynı zamanda sürdürülebilir enerjiye dayalı WPT teknolojisi ile ilgilenen araştırmacılara ışık tutması beklenmektedir.

1. Introduction

The utilization of sustainable energy sources has become more significant in the last decades. The reduced fossil fuel sources and climate changes are one of the most critical concerns needed to be addressed in modern times. Thus, many attempts are available to reduce greenhouse emissions and the usage of fossil fuels. Among them, wireless power transfer technology has drawn attention.

There are many critical issues resulting from the traditional wired power transfer technology, such as safety and feasibility (Abou *et al.* 2018). Considering safety issues, arcs or sparks can occur in bad weather conditions and moving environments. This results in a reduced life span and serious safety events.

Some limitations affect the performance of biomedical applications like potential infection, implant size, and amount of transferred power in conventional wired technologies. With all these problems, WPT technology is put forward to transfer power wirelessly. Thus, WPT technology has more preferred in biomedical applications, underwater, electric vehicles, and high-voltage applications in replace of inconvenient, expensive, and hazardous counterparts.

WPT technology categorizes depending on the transfer distance, namely far-field and near-field technologies. While far-field technology utilizes radiative energy, near-field technology uses non-radiative energy. Far-field WPT is typically preferred in optical power transfer and microwave power transfer applications. Near-field WPT is generally used in inductive and capacitive power transfer applications.

In a nutshell, the investigation has been conducted for the WPT on sustainable energy. The paper is organized as follows. Section 2 presents the history of WPT. The working principle of WPT has been discussed in Section 3. Section 4 includes the sustainable energy-based WPT applications. Section 5 defines the merits and demerits of these applications. Section 6 introduces the proposed solar energy-based IPT system. Finally, a conclusion and discussion are drawn in Section 7.

2. History of Wireless Power Transfer Technology

The history of WPT dates back to experiments carried out by Nikola Tesla in the nineteenth century. However, J. C. Maxwell inspired Tesla by using electricity and magnetism to transport energy via electromagnetic waves. Tesla conducted a series of experimental studies on WPT technology. He first put forward wirelessly powered light bulbs in 1893. Then, Nikola Tesla built Tesla Tower in 1900 (Marincic 1982). One of his experiments based on the WPT is depicted in Figure 1 (Tesla and White 1999). Within the concept of Tesla's study, the primary and secondary resonant circuits are built to maximize the power transfer using an alternating magnetic field. H. V. Noble achieved the first wireless microwave power transfer experiment at a distance of 5 mm in the 1930s (Visser 2017). John Schuler conducted a series of experiments in biomedical applications using WPT technology (Schuler 1961). Brown et al. (1966) studied unmanned aerial vehicles based on microwave WPT technology. Then Peter Glaser put forward the solar power satellite concept (Glaser 1968). Auckland University examined WPT in terms of IPT technology in the 1990s (Boys and Covic 2015). Kurs et al. (2007) from MIT published a study, which covers 60-W wireless power transfer with a transfer distance of 2 m using inductive technology. A myriad of studies since then have been put forward on WPT concept.

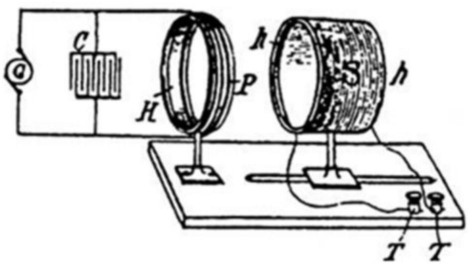

Figure 1. Tesla's WPT prototype.

3. Working Principle of WPT Technology

A general scheme of a WPT system is demonstrated in Figure 2. It consists of primary and secondary sides. While the primary side includes an inverter, primary compensation network, and a transmitter device such as a coil, metal plate, antenna, and light source, the secondary side comprises a receiver device like coil, metal plate, rectenna, and solar cell together with secondary compensation network, rectifier and a DC load (Rim and Mi 2017). Herein, the inverter and rectifier topologies are easily operated in high-frequency in WPT technologies through an air medium. The converter topologies are typically selected by the power level. The class E amplifier structure is usually preferred in both inverter and rectifier topologies whereas the full-bridge inverter and rectifier topologies are typically preferred in high power applications. The compensation networks play a key role in the performance of the WPT system. They are typically formed with LC circuits to provide a higher power factor, lower harmonic components, and lower electromagnetic interference (EMI). The transmitter and receiver devices are designed so that they can efficiently transfer power.

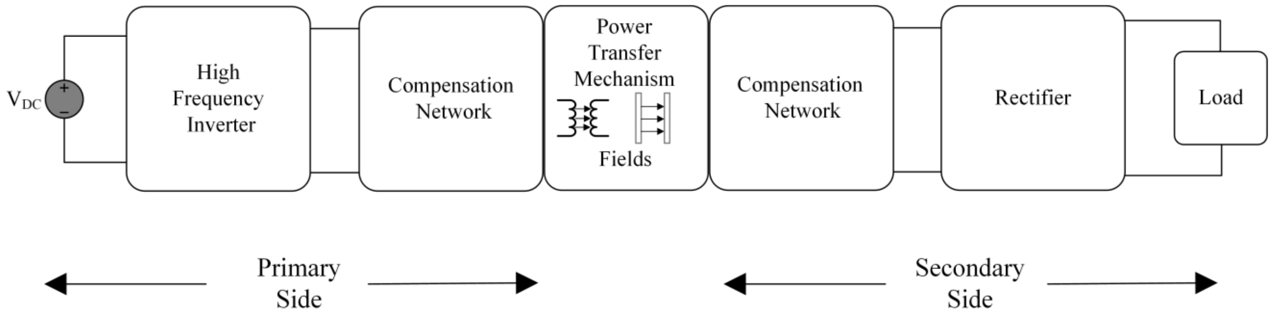

Figure 2. The typical configuration of a WPT system.

Considering the design of coil and metal plates, the mutual coupling term ought to be maximized for given dimensions.

Transfer medium also plays a critical role in the WPT system. Although air is the most utilized medium in many WPT-based applications, water is also used as a medium in underwater wireless charging applications. The dynamic nature of the seawater or ocean can result in variable coupling. For this reason, the misalignment issues are taken into account to provide higher efficiency.

4. Sustainable Energy-based WPT Applications

Wireless power transfer technology is evaluated in the sustainable energy concept under two main topics. The former is solar energy-based WPT applications. The latter is wind energy-based WPT applications.

4.1 Solar energy-based WPT applications

Solar energy-based WPT applications typically utilize microwave power transfer and inductive power transfer technologies. Wang et al. (2022) have drawn attention to laser charging for solar-based WPT applications. While far-field WPT applications use microwave power transfer technology, near-field WPT applications utilize inductive power transfer technology. A satellite solar power station (SSPS) collects solar power via satellites and transfers it to the ground wirelessly by using microwaves (Brown and Eves 1992).

Peter Glaser has been a pioneer of the SSPS concept, then many models were put forward mainly in the USA, Japan, and Europe. Different models are proposed in the SSPS concept. A 5-GW SSPS model was suggested in 1979 by NASA (National Aeronautics and Space Administration) and DOE

(Department of Energy) (Chaudhary and Kumar 2018). In Japan, the JAXA (Japan Aerospace Exploration Agency) and Institute for Unmanned Space Experiment Free Flyer (USEF) are prominent in the SSPS concept (Shinohara 2013). For example, JAXA proposed a 1-GW SSPS model by utilizing microwave transmission at the frequency of 5.8-GHz in 2001.

Chhawchharia et al. (2018) examined solar energy-based WPT technologies, which use inductive power transfer technology. Fareq et al. (2014) proposed a small-scale WPT design using solar energy to transfer power up to 10 cm wirelessly. Zambari et al. (2013) studied solar energy harvesting using inductive power transfer technology to supply wireless power for home appliances. Ojha et al. (2017) evaluated solar-based inductive power transfer technology and highlight the components, such as solar panels, rechargeable batteries, boost circuit topology, and load.

4.2 Wind energy-based WPT applications

Wind energy-based WPT applications typically cover contactless slip rings in wind turbines. Ludois et al. (2012) proposed contactless slip rings instead of mechanical slip rings using wireless capacitive power transfer technology. Ludois has been a pioneer in this field using capacitive power transfer technology. Rezaei et al. (2012) suggested a contactless slip ring to control the pitch angle of the wind turbine using IPT technology. Lohote et al. (2021) discuss wind and solar energy-based hybrid system in IPT technology. Besides the onshore wind energy-based WPT applications, wireless charging solutions are suggested for offshore wind service vessels using IPT technology (Nilsen 2021).

5. Merits and Demerits of Sustainable Energy-based WPT Applications

The advantages and disadvantages of sustainable energy-based WPT applications are presented in this section.

5.1 Merits

- Wireless power transfer technology provides lower cost, higher reliability, and more secure solution along with renewable energy sources.
- Sustainable energy-based WPT technology may decrease the global energy crisis and also lessen the emissions of greenhouse gases.
- Glaser et al. (1998) mentioned that the SSPS concept can ensure 24-h energy among other renewable energy sources. Thus it can be regarded as a sustainable energy source.
- The SSPS provides unobstructed and intact solar irradiance due to its space concept (Chaudhary and Kumar 2018).
- Sustainable energy-based microwave power transfer applications are highly environmentally friendly. They do not include emissions of carbon gases (Maqsood and Nasir 2013)
- Thanks to the integration of sustainable energy-based WPT technology, the electricity bills could be cut to very low.

5.2 Demerits

- Due to the high-frequency microwave signals associated with wireless charging, biological problems can come about in this concept.
- The wireless communication system can be affected by the interference of microwaves.
- The SSPS concept has a high capital cost and high antenna size (Chaudhary and Kumar 2018).
- The SSPS has lower efficiency due to its high transfer distance.
- The solar energy-based WPT technology can only supply power in the daytime.
- The solar energy-based WPT technology needs regular maintenance with the solar panel. Moreover, pollution can cause lower efficiency and decreased power levels.

6. Design and Analysis of Solar Energy-based Inductive Power Transfer System

6.1 Design

Figure 3 represents the solar energy-based IPT system. Solar energy is converted to electrical energy to feed the inverter circuit. The primary compensation network is used to increase the voltage for the resonant circuits. The coils are utilized to form the WPT mechanism. The secondary compensation network is used to decrease the voltage. At last, the rectifier circuit is used to provide the regulated dc voltage for the load. A single PV cell is represented in Figure 4.

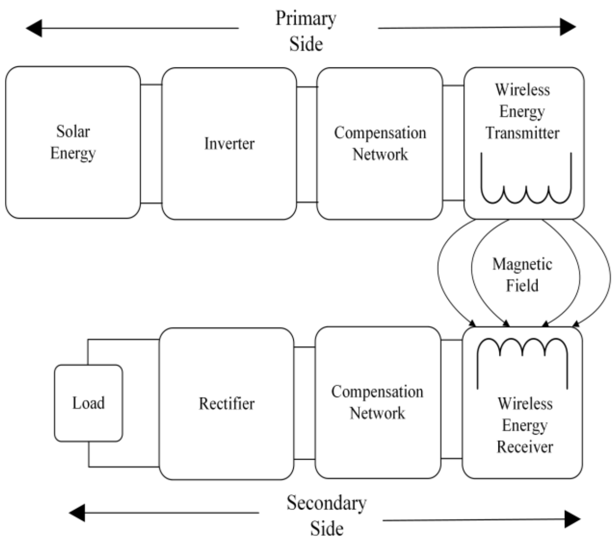

Figure 3. Solar energy-based IPT system.

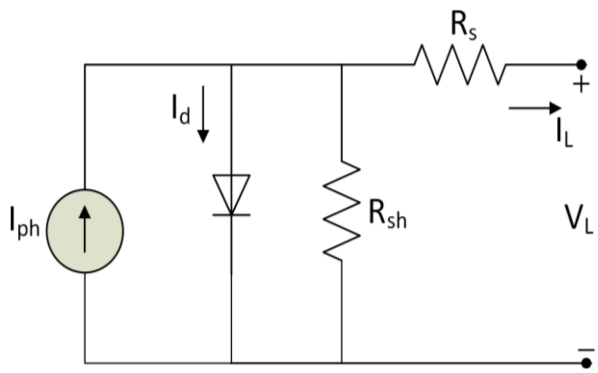

Figure 4. Circuit scheme of a PV cell.

According to the equivalent circuit of a PV cell, the shunt current is obtained by ohm's law:

$$I_{R_{sh}} = \frac{V+IR_S}{R_{sh}} \quad (1)$$

The diode current is represented by the shockley diode equation:

$$I_d = I_0 \left(e^{\frac{q(V+IR_S)}{akT}} - 1 \right) \quad (2)$$

The load current is obtained using Kirchhoff current law (KCL):

$$I_L = I_{ph} - I_d - I_{R_{sh}} \quad (3)$$

$$I_L = I_{ph} - I_0 \left(e^{\frac{q(V+IR_S)}{akT}} - 1 \right) - \left(\frac{V+IR_S}{R_{sh}}\right) \quad (4)$$

The terms q and α represent elementary charge and diode ideality factor, respectively. The open-circuit voltage of the PV cell is represented as given below (Anand and Kannan 2014).

$$V_{oc} \cong \frac{akT}{q} In \left(\frac{I_L}{I_0} + 1\right) \quad (5)$$

4 Trina solar modules (TSM-290 PA14) are used to obtain DC electricity for the IPT system (Amazon, 2022). Thus, a 500-W IPT system at 40 kHz with a quality factor of 4 is designed as given below (Aditya 2016).

$$R_L = \frac{{V_{Srms}}^2}{P_{out}} \quad (6)$$

$$L_S = \frac{Q_S R_L}{w_0} \quad (7)$$

$$I_{Srms} = \frac{V_{Srms}}{R_L} \quad (8)$$

$$I_{Prms} = \frac{P_{out}}{V_{Prms}} \quad (9)$$

$$M = \frac{I_{Srms} R_L}{I_{Prms}\, w_0} \quad (10)$$

$$k < \frac{1}{Q_S}\sqrt{1 - \frac{1}{4{Q_S}^2}} \quad (11)$$

$$L_P = \frac{M^2}{L_S k^2} \quad (12)$$

$$C_{P,S} = \frac{1}{{w_0}^2 L_{S,P}} \quad (13)$$

Table 1. Design parameters of a solar energy-based IPT system.

Parameter	Definition	Value
V_{oc}	Open circuit voltage	44.90 V
I_{sc}	Short circuit current	8.53 A
V_{mpp}	Maximum power voltage	36.10 V
V_{dc}	Input voltage with modules	120 V
V_{out}	Output voltage	48 V
R_L	Load resistance	4. 61 ohm
L_S	Secondary inductance	73.33 uH
M	Mutual inductance	46 uH
k	Coupling coefficient	0.2
L_P	Primary inductance	721.39 uH
C_P	Primary capacitance	21.95 nF
C_S	Secondary capacitance	215.89 nF

6.2 Analysis

The solar energy-based IPT system is simulated using Plexim/Plecs software. Figure 5 depicts the I-V and P-V characteristics of the proposed module. Figure 6 to 8 also represent inverter characteristics.

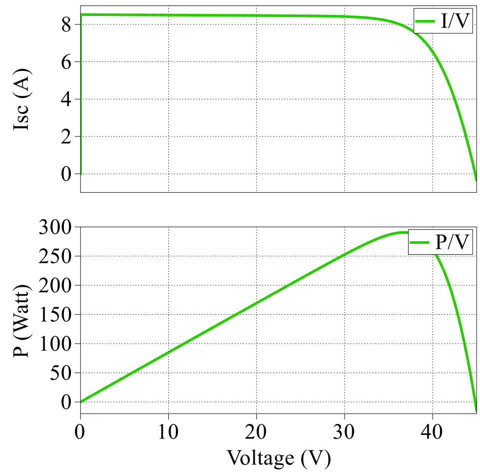

Figure 5. I-V and P-V characteristics of the TSM-290 PA14.

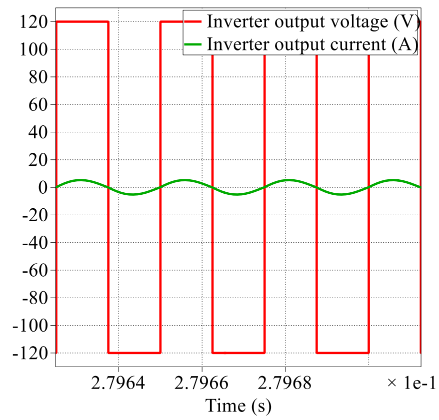

Figure 6. Inverter output voltage and current waveforms.

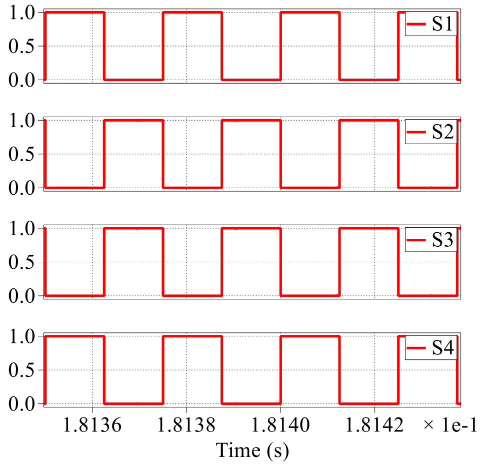

Figure 7. Switching signals of the inverter.

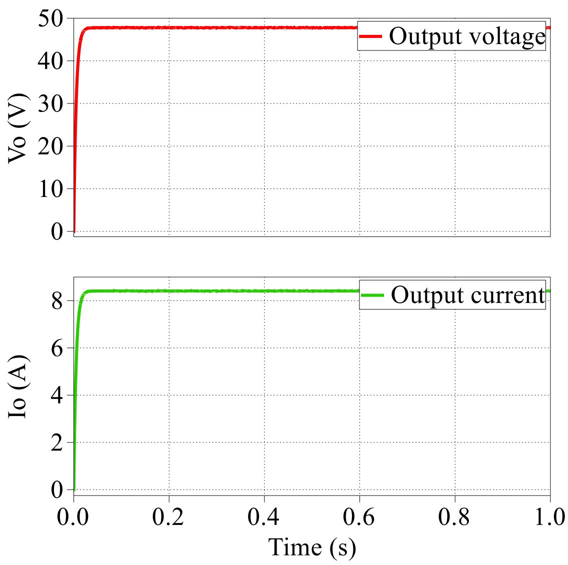

Figure 8. Output voltage and current waveforms.

Each TSM module gives a maximum of 36 V depending on its datasheet. The average value of each module is selected to be 30 V. Hence, four-module provide 120 V dc voltage for the proposed IPT system. The full-bridge topology is used for both inverter and passive rectifier circuits in this solar energy-based IPT system. The obtained results show that PV characteristics are demonstrated successfully. The resonance condition is achieved at the required frequency using a series-series compensation network. Besides, the filter capacitor is utilized to decrease the ripple voltage.

7. Conclusion and Discussion

Wireless power transfer (WPT) technology has drawn attention to sustainable energy-based applications. In this paper, the WPT technology is evaluated in solar energy and wind energy-based applications. Along with the basic working principles of WPT technology, the main advantages and disadvantages of sustainable energy-based WPT applications are also presented. Furthermore, a 500-W solar energy-based inductive power transfer (IPT) system is designed and simulated in the paper. According to the results, a highly effective resonance condition is achieved in the proposed system. Besides, solar energy-based IPT applications stand out among others. While microwave power transfer technology is typically utilized in the satellite solar power station (SSPS) concept, IPT technology is generally used in consumer electronics applications. On the other hand, capacitive and inductive charging technologies are typically preferred in wind energy applications compared to other wireless charging technologies. The most notable advantages of sustainable energy based WPT applications are lower cost, reduced greenhouse gas emissions, and higher reliability. As a suggestion, capacitive power transfer technology can be adapted to solar energy-based WPT applications due to its specific advantages.

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