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Research paper

Computer Simulation Model of High Efficiency Wireless DC Power Supply

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Abstract

This paper presents the computer simulation model of high efficiency wireless DC power supply. The proposed system uses 20 kHz switching frequency of the half-bridge inverter and this value is suitable for the wireless power transfer in order to obtain high efficiency power transfer. In this work, the mutual inductance is used to present the wireless power transfer (WPT) function. The parameter used is based on the actual practical values of Vishay Radial Wireless Charging Transmitter Coil details. This future innovative technology of WPT system is possible to supply electric power especially for mobile or rotating devices without any wire or cable. The WPT system was targeted to achieve power transfer efficiency of higher than 90% between the transmitter and receiver coils. A computer simulation model using MATLAB/Simulink was developed to investigate the behavior and possible inaccuracies of the proposed system.

Keywords: *DC power supply, Wireless power transfer, High frequency inverter, Power transfer efficiency.*

1. Introduction

Wireless power transfer (WPT) topologies have been attractive and got more attention since this method can transfer electrical energy without wire or cable connections [1]. Thus, the removal of the traditional cable connectors or physical connection between power supply and their load can promises to transmit new levels of convenience for the charging of millions electronic devices [2][3]. This is resulting in distinct advantage such as higher safety [4], since this technology do not expose to the electrical wire. Another advantage of WPT is cost reduction due to maintaining direct connectors and safe power transfer to application that need to remain sterile, robust and consistent power delivery to rotating [5].

The demand for WPT today is high due to the application of the wireless power transfer system such as in biomedical implants. Implantable biomedical sensors and actuators are highly desired in modern medicine and the application of wireless power transfer to delivering the electrical power source wirelessly to implant for the last three decades. The other application of this technology is electric vehicle (EV) which is used for wireless battery charging in order to allow the devices to recharge with more safety and conveniently for the user [6]. Other than that, application of wireless power transfer technology is for mobile phone, LED TVs and lightings [4][7]. The telecommunication company had commercialized their smart phone product by using wireless power transfer for the battery charging.

However, there are several problems occurred that can be related to the wireless power transfer (WPT) systems. Power transfer efficiency is the major problem in order to transmit the electrical energy wirelessly. This is due to the air gap between the transmitter and receiver coils. The system losses are high due to the wireless transmission [8]. There are three main aspects need to be considered when outlining the powering strategy of WPT technologies which is small physical volume, high energy efficiency, and compatible aesthetics [9]. These three aspects are the answers of how to supply the energy necessary to operate this network or system.

In this work, the development of wireless power transfer DC supply is considered the switching frequency selection to improve the power transfer efficiency. The proposed wireless power transfers DC power supply uses the selected high switching frequency at 20 kHz because the shielding magnetic field at this frequency is not considered critical to reduce WPT efficiency [14]. The proposed system uses 20V as a DC supply and then the half bridge inverter is used to convert the DC waveform into AC waveform to the transmitter. The high frequency current in the transmitter coil generates an alternating magnetic field, which induces an AC voltage on receiver coil [5]. The development of mutual inductance on the power transmission by using the parameters from the actual practical values of Vishay Radial Wireless Charging Transmitter coil [15] can improve the efficiency of the power transmission system. The receiver coil then receives the AC waveform and convert back to DC waveform by using high-frequency full bridge rectifier for the DC load.

2. WPT technology

WPT is the transmission of electrical energy without wires or any medium except air and this transmission technology use time-varying electric, magnetic or electromagnetic fields [1]. WPT concept can be referring as Lentz's Law which states that time variant magnetic field around it which is at the transmitter [5] as shown in Figure 1. The typical topology of Lentz's Law is the direction of current in a conductor loop induced indirectly by the change in magnetic flux through the loop. The charges in the conductor are not pushed in motion directly by the change in flux, but by a circular electric field surrounding the total magnetic field of inducing and induced magnetic fields. This total magnetic field will induce the electric field.

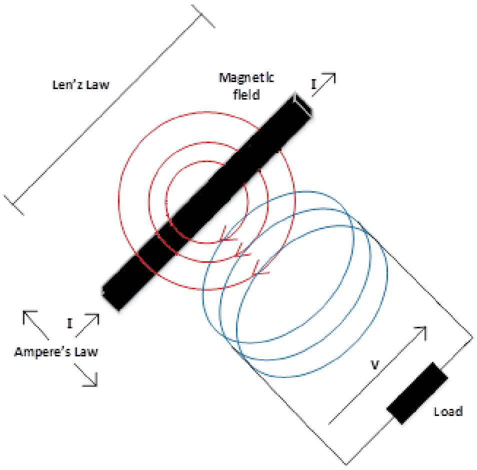

Fig. 1: Block diagram of WPT concept.

In WPT system, there are two magnetic couplers that wirelessly transfer power. The first magnetic coil at the primary side called the transmitter coil, while the second coil at the secondary side is called the receiver or pickup. To obtain higher power transfer efficiency, it is important to have high coupling coefficient, k and quality factor, *Q*. Quality factor is the ratio between resonant frequency, ω_0 and its intrinsic loss rate, Γ. Thus, the thicker the wire and the larger the ferrite section area was, the higher quality factor would be. By referring Equation (1) [12], high frequency usually adopted to increase the value of *Q*.

$$Q = \frac{\omega_0 L}{R} \tag{1}$$

The coupling coefficient, *k* is significantly affected by the design of the magnetic couplers and it can be considered as one of the most important factors to improve power transfer efficiency in a WPT system [13]. Theoretically, the larger the size of gap ratio of the coupler, the higher the value of *k* would be. Apart from the frequency, the coupling coefficient, *k* is significantly affected by the design of the magnetic couplers that considered as one of the most important factors in a WPT system. The value of coupling coefficients can be determined by Equation (2) [12].

$$k = \frac{Mi}{\sqrt{L1L2}} \tag{2}$$

The mutual inductance, M_i between transmitter and receiver is determined by the core material, the number of turns, and geometry. A thorough analysis of magnetic field distribution may yield this parameter but an easier way is to measure the induced voltage at the receiver coil before determining the mutual inductance with the following Equation (3) [12]. V_{so} is the value of open circuit voltage at secondary loop, I1 is the value of current for the primary loop and ω can be considered as resonant frequency from the proposed system.

$$\mathrm{Mi} = \frac{V_{so}}{\omega I_1} \tag{3}$$

Figure 2 shows the relationship between M_i, V_{so}, and I_1.

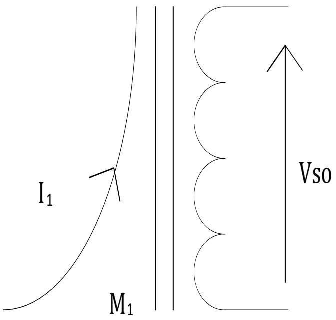

Fig. 2: Open circuit voltage of the receiver coil.

The induce current from the supply will flow through the transmitter inductive coil and provide magnetic fields. Mutual inductance represented as a transmitter coil that transmits the electrical power into the receiver coil. The receiver coil will then captures the magnetic fields and induced the voltage as supply for the secondary part [6]. The use of DC capacitor as a filter leads to get the pure DC waveform with the specific value of the capacitance [14] [15]. As a result to complete the WPT system, load that connected to the receiving part will flow by the current from the transmission of the system.

3. Research method

There are several methods that have been reported to solve the low power transfer efficiency problem in WPT. Such methods uses a high switching frequency, impedance matching and resonant circuit to increase the magnetic flux in the receiver [1] [7] [17] [22]. Other methods uses high permeability material such as ferrites that can improve the magnetic coupling and two intermediate coils with capacitors to increase magnetizing impedance between the transmitter and the receiver coils, thus, improve the power transfer efficiency [23].
The proposed WPT power supply system begin with the investigation of the ground work of the WPT system. The theoretical model of high efficiency WPT DC power supply has been proposed by the preliminary research. The computer simulation circuit model of the proposed system has been design by using MATLAB/Simulink. Selected simulation results are presented with the related theory and hypothesis.

4. Proposed system

The proposed WPT system is as shown in Figure 3. This system uses 20V supply voltage and was divided into two main parts which is the transmitter and receiver. In the transmitter part, it consists of the high frequency half-bridge inverter that was connected in parallel with a primary compensation circuit, *CS1* and the transmitter coil [24]. The half-bridge inverter was form by using two power MOSFET, labelled as *M1* and *M2*. Then, the receiver part have the receiver coil with the secondary compensation capacitor, *CS2*, and a high frequency full-bridge rectifier.

4.1. Circuit operation

The principal operation of WPT DC power supply had several stages to transmit the supply electrical energy to the load wirelessly. As shown in Figure 3, the propose WPT system consists of three part which is half bridge inverter, wireless power transfer and high frequency full-bridge rectifier. During the transmitter stage of operation, the DC supply is converted into the AC form by using high frequency half-bridge inverter. In this work, the high switching frequency of 20 kHz was used [10]. Then, the high frequency current that flows through the transmitter coil will generate an alternating magnetic field. Then, the energy that have been transmitted in high frequency AC current will be induced at the receiver coil that connected in parallel connection with secondary compensation capacitor, *CS2* [14] [15]. The AC voltage is then converted into DC form by using high frequency full-bridge rectifier to supply the DC load. Hence, capable to transmit the electrical energy to the load wirelessly.

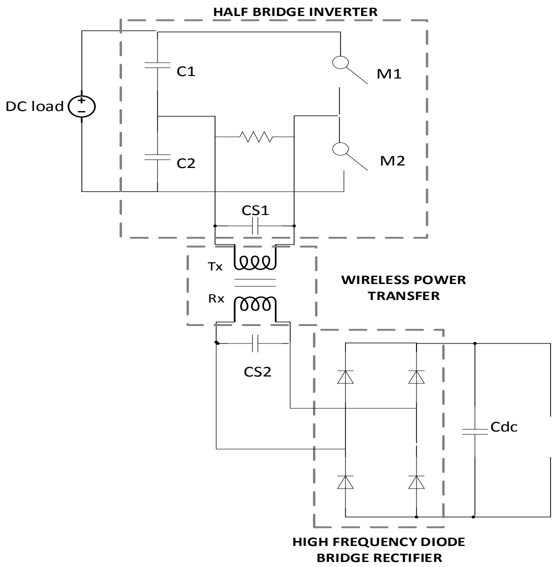

Fig. 3: Block diagram of propose wireless power transfer (WPT).

4.2. System setup and parameters

Table 1 shows the parameters of the proposed system. The input DC source of the proposed wireless power transfer is 20V. The mutual impedance, M_i of the transmitter and receiver coils are determined based on the core material, the number of turns and geometry. The parameters of transmitter and receiver coils winding have been determined based on the Vishay Radial Wireless Charging Transmitter Coil IWTX-4646BE-50 model [11]. The calculation of the mutual inductance M_i is based on the Equation 3 [10] where V_{so} is the value of open circuit voltage at secondary loop, I_1 is the current value of the primary loop and ω can be considered as resonant frequency from the proposed system. The calculation of the quality factor, Q is based on Equation 1, while the coupling coefficient, k was determined based on the Equation 2. The detail parameters value and the mutual inductance are as shown in Table 1 and Table 2 respectively.

Table 1: System Parameters

Parameters	Value
Voltage Supply	20V
Switching Frequency	20kHz
Transmitter and receiver coils inductance	0.3mH
Compensation Capacitor	0.6µF
Coupling coefficient, k	12.5
Quality Factor, Q	42.48

Table 2: Mutual Inductance Parameters

Parameters	R (Ω)	L (H)
Winding 1	0.071	24µ
Winding 2	0.071	24µ
Mutual Inductance	1	0.3m

The power transfer efficiency of the proposed system was determined based on the Equation 4 [10]. From Equation 4, the value of coupling coefficient, *k*, of the mutual inductance was used. The Q_1 represents the quality factor at transmitter coil, while the Q_2 is the quality factor at the receiver coil. Based on Equation 4, the power transfer efficiency between the transmitter and receiver coils of 98.14% was obtained. This value can be considered as a high efficiency wireless power transfer.

$$\eta = \frac{k^2(Q_1 Q_2)}{(1+\sqrt{1+k^2(Q_1 Q_2)})^2} \quad (4)$$

5. Computer simulation model

The proposed circuit model was simulated by using MATLAB/Simulink software as shown in Figure 4. This circuit model was composed from two parts. The first part (transmitter) consists of DC power supply, high frequency half-bridge inverter, pulse width modulation (PWM) block diagram and a transmitter coil. The second part (receiver) consists of receiver coil and high frequency full-bridge rectifier. Figure 5 shows the pulse width modulation (PWM) circuit model. The block diagram of repeating sequence is used as a function of carrier signal and to set the switching frequency of 20 kHz. Then, this signal is compared with the constant block set as a function of modulation index to generate the desired PWM signals [25] [16]. Thus, this PWM signal is used to control the switching sequences of the half-bridge inverter.

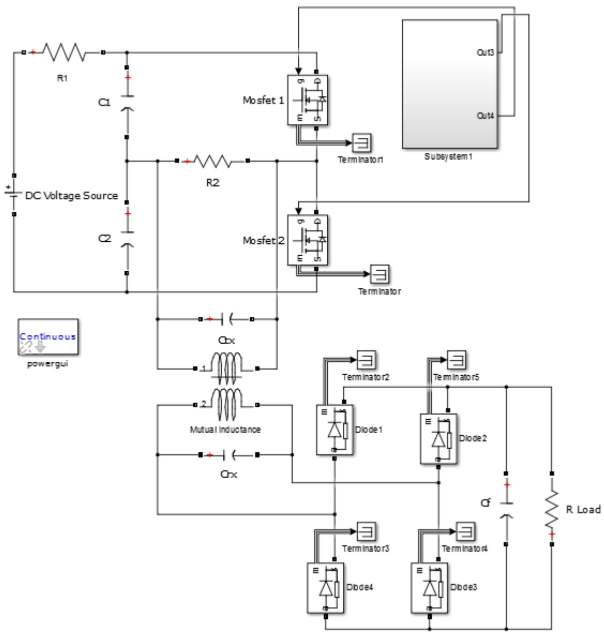

Fig. 4: Circuit model of high efficiency wireless DC power supply.

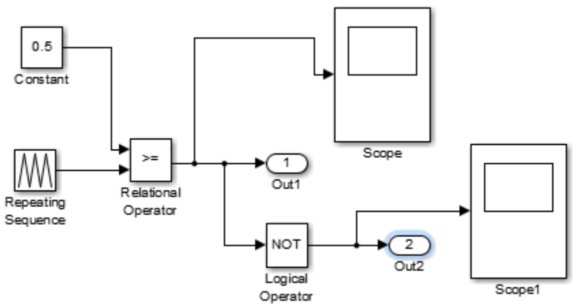

Fig. 5: Block diagram of PWM in MATLAB Software.

6. Results and discussion

Figures 6 and 7 show the generated PWM signal for the first and second cycles operations to control the turn-*ON* and turn-*OFF* of transistors for the half-bridge inverter. The input voltage is set to 20V. The high frequency *AC* voltage at transmitter coil is as shown in Figure 8, while, Figure 9 shows the output *DC* voltage waveform of the proposed converter. From the result obtained in Figures 8 and 9, the output voltage is 9.3V. This value is slightly lower than 10V and accurs due to the intrinsic semiconductor losses. The efficiency of the power transfer between the transmitter and receiver coils of 98.14% was obtained based on Equation 4.

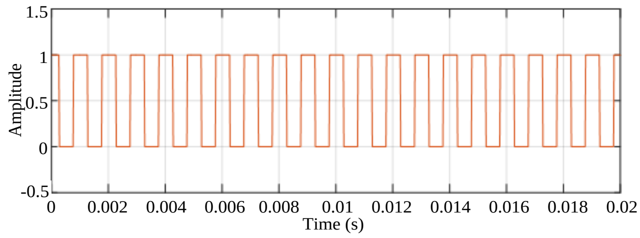

Fig. 6: First cycle of PWM switching.

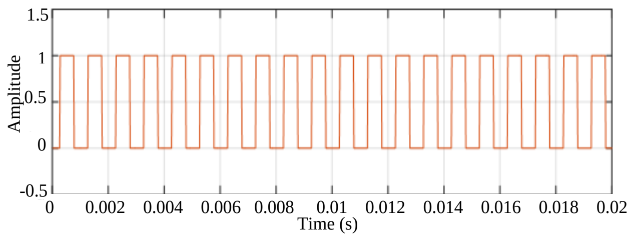

Fig. 7: Second cycle of PWM switching.

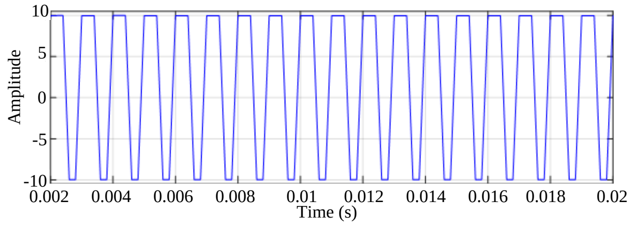

Fig. 8: High switching frequency AC waveform at transmitter.

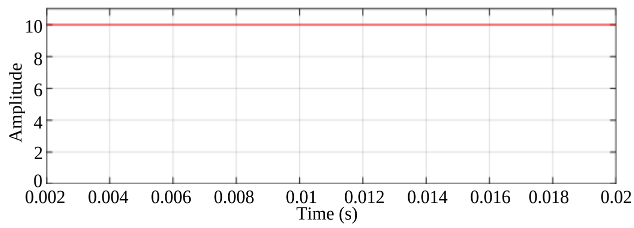

Fig. 9: DC voltage output waveform.

7. Conclusion

This paper discuss the development of high efficiency wireless DC power supply system. Detailed description of the circuit simulation model for the proposed system has been presented with the related mathematical treatment. The power transfer efficiency between the transmitter and receiver coils of more than 90% was obtained, where this value is good in power electronic converter design. The power transfer efficiency of the proposed operation is discussed with the synthesized output envelope presented. As a result, such theoretical enhancements can be used as a novel foundation of the future wireless power supply sytem.

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