Investigation of Wireless Power Transfer for Smart Grid On-line Monitoring Devices Under HV Condition

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Abstract

Magnetically coupled resonant wireless power transfer (WPT) has been employed in many applications, such as wireless charging of portable electronic devices and electric vehicles. This technology can also provide solutions for power transfer in complex environment and special scenario with mid-range transfer distance and acceptable transfer efficiency. In this paper, a mid-range WPT system is designed to provide an effective solution for power supply to smart grid on-line monitoring devices in high voltage (HV) on-site condition. Both the model, design, and experimental implementation of a two-coil system are represented. To find out the transfer characteristic of the proposed mid-range WPT system, the circuit model, exciting frequency, coupling, output power and transfer efficiency are analyzed based on the circuit and magnetic principles. Some key points about the optimal working area for the mid-range WPT system are demonstrated. Finally, a prototype system with transfer distance 1.1 meter for 110 kV HV power cables is built to verify the effectiveness of the regular law of system. By carefully tuning the circuit parameters, the prototype is able to deliver 20W power through 1.1 meter distance with 20.23% efficiency.

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Keywords: Wireless power transfer (WPT), Mid-range, Smart Grid, HV power, On-line Monitoring Devices

1. Introduction

Wireless power transfer (WPT) technology is promising in many industrial applications in case that the interconnecting wires are inconvenient, dangerous, or even impossible. The concept of WPT technology was first...
proposed by Nikola Tesla more than a century ago. In 2007, a 9.9 MHz WPT scheme using strongly coupled magnetic resonance systems (CMRS) was introduced whose power transfer level and coil-to-coil efficiency are 60 W and 45%, respectively, at a distance of 2 meters. The system adopted large self-resonant coils at each primary and secondary side to induce a large magnetic field to obtain an extended transfer range. For the high current in these self-resonant coils, the internal resistances of the coils must be very small. This means that the coils must have very high Q factors, which consequently result in very thick wires. Furthermore, the stray capacitances and inductances are too sensitive to surroundings such as temperature, humidity, and human proximity, which leads the system to a poor robustness. These characteristics are why the well-known CMRS is seldom used in high-power applications. In practical use, previously reported WPT applications concentrated on portable electronic devices and electric vehicles, which power transfer distances were within a range of several millimeters (mm) upto dozens of centimeters (cm). So far, the mid-range or long distance power delivery WPT systems are rarely investigated.

In power industry, due to the importance of HV cables in the transmission network, on-line condition monitoring is a very important issue. However, the power supply is always a key problem for the reliability of the monitoring devices which operate in harsh outdoor environment with no reliable power sources. Therefore, this issue is one of major problems in the construction of smart grid. Conventional applications tries to use the solar and wind power to solve the problem, but these power sources are not guaranteed in case of continuous bad weather condition which could occur frequently in some places like the mountain areas. However, the WPT technology may work in the above conditions as a stable and reliable power sources. For this kind of applications, the key requirement is to transfer sufficient power to the load with a relative high power transfer efficiency and considerable distance. In addition, robustness and reliabilities are also important issues especially for case of the HV cables monitoring. A possible installation of WPT system on the towers with transferring power through the insulator to the monitoring devices, as shown in Fig. 1. The power collection is from HV lines using traditional methods by current transformer (CT). Then the electric power is transferred to devices by the mid-range WPT technology.

![Fig. 1. A possible installation method for HV lines (a) schematic; (b) real picture.](image)

In this paper, a two-coil WPT solution for the power supply application of HV lines monitoring devices is presented. The proposed WPT system works in relative low frequency range (less than 1MHz). To optimize the system characteristic, the practical parameters of coils design and circuit models are analyzed, calculated, and implemented. The optimal parameters design for the mid-range WPT system including coils, circuit model, frequency and load are discussed. A WPT prototype designed for practical 110 kV HV power lines monitoring is set up. By carefully tuning the circuit parameters, the prototype is able to deliver 20W power through 1.1 meter distance with 20–30% efficiency. The proposed prototype is promising to be a good candidate using as power supply for smart grid on-line monitoring devices with the advantages of robustness, reliabilities, install convenience and low costs.

2. Circuit design and analysis

The basic circuit of the WPT system is shown in Fig. 2(a). This circuit is fundamentally the same as the circuit model of transformers. In the circuit, a larger mutual inductance $M$ facilitates more effective power transfer. The mutual inductance $M$ is determined by $L_1$, $L_2$, and the coupling coefficient $k$, as follows:

$$M = \frac{\mu_0}{4\pi} \iint_{S_1} \iint_{S_2} \frac{\mu_0}{R} dl_1 dl_2 = k \sqrt{L_1 L_2}$$  \hspace{1cm} (1)
where $k$ indicates the degree of coupling strength and is between zero and one. However, $k$ of a WPT system for mid-range applications is very small due to the large air gap distance between two resonant coils, which is necessary for complex environment and special scenario.

![Diagram](image)

**Fig. 2.** The proposed WPT system (a) actual equivalent circuit (b) calculation $k$ of two helix coils and (c) equivalent circuit model.

Here, helix coils are designed for the proposed WPT system because of their magnetic principle and simple fabrication. The radius of the two coils is 20 cm. They are wound by 17 turns using Litz cable with 1200 strands. The investigation of system transmission performance should begin with the analytical analysis of the mutual inductance and coupling coefficient. The mutual inductance $M$ can be calculated through the function defined as (1), then coupling coefficient $k$ can be calculated. According to (1), the $M$ between two circle coils can be obtained by approximate superposition calculation, making more convenient to characterize the transfer function of WPT system in theory. Additionally, the function of coupling coefficient $k$ versus transfer distance $d$ is shown in Fig. 2(b).

Generally, capacitors are inserted to resonate with coils and overcome the returned magnetic field and low efficiency in WPT system. These capacitors make the circuit resonate at the operating frequency and minimize the circuit impedance. It is called as compensation. There are four basic compensation topologies for primary and secondary sides: SS compensation, SP compensation, PP compensation, and PS compensation, where S denotes series compensation and P denotes parallel compensation. Series compensation has voltage-source characteristics, and parallel compensation has current-source characteristics. The four compensation topologies have four different reflected impedances. The required primary compensation capacitors for the reflected impedances were well analyzed in reference 6. According to the analysis, for a mid-range WPT system applications, the use of SS compensation is recommended, because the required small load and the primary compensation capacitor depends on the mutual inductance $M$ and load resistance $R_L$ in SP, PP, and PS compensations. Fig. 2(c) shows the equivalent circuit model of the two-coil WPT system, where the coil system with self-inductance $L_1$ and $L_2$, copper loss $R_1$ and $R_2$, and compensated capacitors $C_1$ and $C_2$. $R_s$ is the impedance of the AC power source $V_s$. $R_L$ is the load resistance of the output.

For the SS-system shown in Fig. 2(c), the optimal parameters which maximize the WPT are analyzed in reference 6. The two-coil model can be analyzed using Kirchhoff’s voltage law (KVL) as follows:

$$ (R_1 + R_s + joL_1 + \frac{1}{joC_1})I_1 - joMI_2 = V_s $$

$$ -joMI_1 + (R_2 + R_s + joL_2 + \frac{1}{joC_2})I_2 = 0 $$

$$ \eta = \frac{|I_1|^2 R_1}{|I_1|^2 (R_1 + R_s) + |I_2|^2 (R_2 + R_s)} = \frac{R_1\omega^2M^2}{[(R_1 + R_s)^2 + (\omega L_1 - \frac{1}{\omega C_1})^2](R_2 + R_s) + \omega^2M^2(R_2 + R_s)} $$
\[ P = \frac{V^2 E^2 R_L}{(E^2 + AC - BD)^2 + (AD + BC)^2} \]

where \( A = R_S + R_1, B = \omega L_1 - 1/\omega C_1, C = R_L + R_2, D = \omega L_2 - 1/\omega C_2, \) \( E = \omega M, \) \( \eta \) is efficiency of the WPT system and \( P \) is the output power. In the paper, a Microtest 6630 Impedance Analyzer (made in Taiwan) is used to measure the coil parameters. The measured coil parameters are shown in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance</td>
<td>312.6 ( \mu )H</td>
<td>308.7 ( \mu )H</td>
</tr>
<tr>
<td>Capacitance</td>
<td>204.4 pF</td>
<td>206.5 pF</td>
</tr>
<tr>
<td>Resistance</td>
<td>1.76 ( \Omega )</td>
<td>1.64 ( \Omega )</td>
</tr>
<tr>
<td>( R_L )</td>
<td>10 ( \Omega )</td>
<td>—</td>
</tr>
<tr>
<td>( k )</td>
<td>0.0001 to 0.1</td>
<td>—</td>
</tr>
<tr>
<td>( V_s )</td>
<td>20 V</td>
<td>—</td>
</tr>
<tr>
<td>AC frequency</td>
<td>600 to 660 kHz</td>
<td>—</td>
</tr>
</tbody>
</table>

The transmitter coil (Tx) and receiver coil (Rx) sides have approximate equivalent inductance and capacitance, so they share the same resonant frequency as required in \( \omega_0 = (L_1C_1)^{1/2} = (L_2C_2)^{1/2} \). However, for the resistance part, there is little flexibility for the parameter changes. All the resistance values such as \( R_S \), \( R_1 \), \( R_2 \) are the practical measurement from the test. Normally the transfer distance between the two coils can be several times of the coil radius, which makes the coupling coefficient \( k \) a very small value around 0.001 to 0.01. Only a small amount of the flux generated by Tx coil is able to go through the Rx coil. However, a large amount of magnetic energy can still be transferred through the limited amount of flux with relatively high efficiency (around 20 to 30%) when the Rx and Tx coils are in the resonant state. This phenomenon can be explained by the circuit and magnetic theory.

Fig. 3. (a) Efficient and (b) output power as a function of frequency and coupling coefficient \( k \) using the parameter given in Table 1.

According to data in Table 1, the efficient and output power against the exciting frequency and coupling coefficient can be plotted in Fig. 3. When the coil distance is short and coupling coefficient between the two coils is big, the WPT works in the over coupled regime. The power transfer efficient of WPT system monotonically drops with the decrease of coupling coefficient. Obviously, once transfer distance exceeds a critical coupling point, the power transfer efficiency drops sharply, as shown in Fig. 3(a). In Fig. 3(b), frequency splitting can be clearly observed as there are two peak output powers. When the coupling between the two coils decreases with the increment of the distance, the system goes into the under coupled regime. The frequency separation between the two peak values decreases until they converge at a single frequency \( f = f_0/(1-k^2)^{1/4} \), where \( f_0 \) is the resonant frequency of both coils. It is noted that the above discuss is under the condition of a fixed load. In fact, the values of efficiency and output power vary with load \( R_L \).
3. Experimental implementation of mid-range WPT systems

3.1. Main circuit and practical design

Fig. 4(a) is the configuration of SS-compensated practical application of the proposed WPT system. A STM32 MCU (microcontroller unit) controller is adopted to generate the accurate square wave exciting signal. The frequency signal is amplified by a gate driver module and then drives a MOSFET H-bridge to generate a high frequency AC. The Tx coil is energized by the AC and transmits the power to the Rx coil though the inductive coupling. The high frequency AC is rectified to DC using bridge rectifier on the Rx side. The DC is filtered by capacitors before it drives the load. Two helix coils are designed for the practical WPT system as above discussed. The radius of the two coils is 20 cm. They are winded by 17 turns using Litz cable with 1200 strands, which forms inductance of 312 $\mu$H. Low resonant frequency requires bigger capacitance as well as big inductance, which means the parasitic capacitance of the coil winding itself is not big enough and add-on capacitors connected in serial with the winding are necessary. As shown in Table 1, a 200 pF high voltage ceramic capacitor is used to meet the target resonant frequency.

![Fig. 4. (a) Main circuit of the proposed WPT system and (b) experiment setup](image)

The practical coil design makes the whole WPT system switch at 610 kHz which is within the range of ultra-fast MOSFET. A MOSFET H-bridge is built to amplify the high frequency signal generated by the STM32 module and energizes the Tx coil to transmit the electric power. On the Rx side, due to the high working frequency, conventional diodes are not fast enough to rectify high frequency AC without inducing significant losses. Therefore, the electric energy received by the coil is rectified to DC by a high speed bridge rectifier made of Shockley diodes. Shockley diodes have very small reverse recovery time (less than 50 ns), which reduces the loss greatly at the high working frequency. For experiments, a 60V 10A DC power supply is simulated as a practical CT, which can pick electric energy from HV lines. Experimental setup of the resonant system is depicted in Fig. 4(b). The full-bridge high frequency inverter and rectifier are used in the experimental prototype. The resonant coils system actually operates like a very sensitive band pass filter. Even though the full-bridge inverter can only generate square waves, only the fundamental frequency is able to go through and other parasitic frequencies are cut off. On the Rx side, a 120V 300W variable electronic load is connected to the rectifier filter module.

3.2. Experimental results

The resonant frequencies of the Tx and Rx coils are well matched by adjusting both circuits carefully. The input power, load voltage, and load current are measured. Therefore, both the output power and overall efficiency (with the loss on the power electronics) can be calculated. Using this prototype, the WPT experiments at the distance of 0.5-1.1m are conducted with a fixed load 50\(\Omega\). In addition, the efficiency of the system is also measured and calculated at the distance 1.1m with variable loads. The experimental results are shown in Fig. 5. Obviously, the efficiency dropped sharply with the increasing of transfer distances. There is an optimal load value for the efficiency and output power of the WPT system. In the experiment, it is also note that high transfer efficiency (more than 20%) can be maintained for a quite wide range about 6 kHz. Because the coupling is bigger than the critical value, the
output power does not reach the maximum at the resonant frequency when the resonant frequencies are well aligned. The frequency splitting can be observed clearly as there are two peaks for the output power which are placed on both sides of $f_0$, which is indicated from the circuit analysis in section 2.

Fig. 5. Experimental results. (a) efficiency versus transfer distance (b) efficiency versus load at the distance 1.1m.

4. Conclusion and future work

In conclusion, to achieve an effective solution for power supply to smart grid on-line monitoring devices in high voltage (HV) on-site condition, a mid-range WPT system is investigated by both theoretical analysis and experiments. The circuit model and implementation of a practical two-coil WPT system have been introduced. Using the circuit theory, the relationship between the circuit parameters, coupling coefficient power transfer, output power and efficiency are analyzed. The optimal working area balancing the efficiency and distance is recommended based on the analysis. A experimental prototype with mid-range transfer distance from 0.5-1.1 meter is built to verify the effectiveness of the regular law of system. By carefully tuning the circuit parameters, the prototype is able to deliver 20W power through 1.1 meter distance with 20.23% efficiency. In our future work, the transfer distance of the proposed WPT system will be extend to about 3.0 meter by frequency tracking technique. We believe that the system, which can be purchased easily from the market with very low costs, can find widely applications in future wireless technology in smart grids.

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References