1. Introduction

Wireless Power Transfer (WPT) method can eliminate all the charging problems of Electrical Vehicles (EV)\(^1\),\(^2\). Through WPT technology, Electrical Vehicle charging becomes an easy task by parking the vehicle at the charging station. Recently Inductive Coupled Power Transfer (ICPT) technology is widely used for WPT in Electrical Vehicles. ICPT consists of compensating capacitors and coupled inductor with a large air gap between them\(^3\).

When the inductor windings share a magnetic core, the entire flux produced by one winding gets linked with the other winding. Due to this phenomenon, tightly coupled network is used for transferring the power efficiently. Instead, if the coils do not share the magnetic core or separated with a large air gap, the flux linking the secondary coil will be very less which in turn reduces the power transfer through the coils\(^4\). However, these coils can be maintained at a resonating frequency to overcome the low efficiency in WPT system. A capacitor is added on both sides of the coupled inductor to maintain the inductors at resonance. This is termed as compensation.

Since various reactive components contribute to resonance, many resonating frequencies exist in the system. Compared to other frequencies, resonant frequencies have different characteristic features. Hence, a careful study on resonant circuits at various frequencies is essential to understand the WPT system\(^5\).

Out of the various compensators, frequency analysis of Series-Series (SS) compensator is carried out and this compensator is chosen for the wireless power transfer. Along with WPT, PV array can be combined to provide an eco-friendly method of charging EV. PV cell converts the solar energy into electricity in a clean, reliable and quiet way without any pollution\(^6\),\(^7\). Hence, the PV array can be used to provide the primary source of energy for...
the WPT system. Considering all the above factors, the proposed system is designed to extract the power from PV array and convert the PV voltage into a high frequency AC voltage by means of an inverter and transfer the power to the battery charging circuit through inductive power transfer technology and rectifier.

2. Proposed SS-WPT System

The proposed Series-Series-Wireless Power Transfer (SS-WPT) system consists of a PV array, H-bridge inverter, Magnetic coupled network, a full bridge diode rectifier, a capacitive filter and a load as shown in Figure 1. The full bridge inverter which is connected to PV array converts the dc voltage to a high frequency ac voltage.

![Figure 1. Series-Series compensator of WPT system.](image)

The loosely coupled primary and secondary winding is shown as a coupled inductor with a coupling coefficient of 0.2. Capacitors, C1, C2 are connected in series with the coupled inductors to realize the SS compensator.

For obtaining the constant ac voltage signal at secondary side of coupled network, a capacitor, C3 is connected in parallel. This constant voltage is given to diode bridge rectifier which converts constant ac voltage to desired dc voltage. This dc voltage is used to charge the EV battery of appropriate rating.

2.1 Frequency Analysis

As various inductors and capacitors contribute to resonance in compensation network, three different resonating frequencies exist. From the literature, it is found that the preferred resonant frequency can be divided into two categories: (i) resonant frequency by self-inductance and series capacitor$^{10-17}$, and (ii) the other resonant frequency by leakage inductance and series capacitors$^{18-21}$.

From the frequency analysis$^6$, three different resonant frequencies are obtained as given below:

\[ \omega_{01} = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \]  
\[ \omega_{02} = \frac{\omega_{01}}{\sqrt{(1 - k)}} \]  
\[ \omega_{03} = \frac{\omega_{01}}{\sqrt{(1 + k)}} \]

It was observed that at first resonant frequency ($\omega_{01}$), the voltage gain changes with the change in quality factor. That is, if the load changes, the voltage gain also changes. But, at other two resonant frequencies ($\omega_{02}$, $\omega_{03}$), the voltage gain is always 1 irrespective of the load variations.

The first resonant frequency is fixed while the second
and third resonant frequencies are determined by the coupling co-efficient (k). As the voltage gain is always 1 at second resonant frequency, $\omega_{02}$ is preferred in power electronic applications, whereas $\omega_{03}$ is preferred in other applications.

The values of the coupled inductor and the series capacitors are designed using the first resonant frequency ($\omega_{01}$). For effective power transfer, the inverter should be operated at second resonant frequency ($\omega_{02}$).

### 3. Simulation Studies and Results

The proposed SS-WPT system is modeled and simulated in PSIM software as shown in the Figure 2.

#### 3.1 H-Bridge Inverter

H-Bridge inverter consists of four switches as shown in Figure 2. When $Q_1$ and $Q_4$ are triggered, a positive voltage will be appearing at the output and when $Q_2$ and $Q_3$ are triggered, a negative voltage will be appearing at the output terminals of the inverter. This square signal is given to magnetic coupled network also referred as resonating tank. The square wave can be defined as

$$V_{pri}(t) = V_{tr}(0 < \omega t < \pi)$$

$$= - V_{tr} (\pi < \omega t < 2\pi)$$

The operating frequency, $f_{02}$ of inverter is chosen as 50 kHz.

#### 3.2 Magnetic Coupled Network

The values of coupled inductors and compensating capacitors are designed as per the equations (1) & (2) with the first resonating frequency $f_{01}$ as 45 kHz. The designed values are shown in the Table 1.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Parameters</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$N_1:N_2$</td>
<td>1:1</td>
</tr>
<tr>
<td>2</td>
<td>$C_1:C_2$</td>
<td>0.1 uF</td>
</tr>
<tr>
<td>3</td>
<td>$L_1:L_2$</td>
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<td>4</td>
<td>Mutual Inductance</td>
<td>25.3 uH</td>
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<tr>
<td>5</td>
<td>Coupling Co-efficient</td>
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</tr>
</tbody>
</table>

Using the designed values, simulation studies of the proposed system is carried out and the results are presented in this section. PV array voltage, $V_{pv}$ and current, $I_{pv}$ was found to be 32.4V and 3.2A respectively as shown in Figure 3.

The voltage waveforms of primary and secondary sides of coupled inductor are shown in the Figure 4. From the results, it was found that the voltage gain of coupling network is almost equal to 1.

The waveforms of primary side voltage, $V_{pri}$ and current $I_{pri}$ are shown in Figure 5(a). Secondary voltage $V_{sec}$ and secondary current $I_{sec}$ are shown in the Figure 5(b). The load voltage $V_0$ & output current $I_0$ are shown in Figure 5(c) which was found to be 32.7V and 3.1A respectively.
4. Experimental Investigation

The prototype of the proposed system is fabricated in the laboratory and the photograph of the experimental setup is shown in Figure 6. The gate pulses were generated using PIC18F45K20 microcontroller and fed to the MOSFETs using the gate driver IC IR2110. The gate pulses to the Metal Oxide Semiconductor field effect transistor (MOSFETs) in the inverter are shown in the Figure 7. A small dead time in the gate pulses has also been introduced to avoid the short circuit in the inverter.

As per the designed values, two air core spirally wounded inductors were fabricated in the laboratory as shown in Figure 6. It was found that the variation of coupling coefficient with respect to distance between the coils is very less due to the spiral winding. Wireless power transfer is ensured by testing the proposed system upto the secondary terminals of magnetic coupled network, with the conventional dc supply and resistive load. The experimental results are furnished in this section.
5. Conclusion

In this paper, a system is proposed for charging the battery from PV array in WPT mode. Detailed frequency analysis is carried out for the SS compensation network and the proposed system is simulated using PSIM software. Laboratory prototype is developed and experimental investigation is carried out to validate the simulation results. Both experimental and simulation results correlate with each other resulting in the successful working of the proposed system.

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7. References