Constant voltage and constant current control implementation for electric vehicles (EVs) wireless charger

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Abstract. This paper presents the implementation of Constant Voltage (CV) and Constant Current (CC) control for a wireless charger system. A battery charging system needs these control modes to ensure the safety of the battery and the effectiveness of the charging system. Here, the wireless charger system does not employ any post-regulator stage to control the output voltage and output current of the charger. But, it uses a variable frequency control incorporated with a conventional PI control. As a result, the size and the weight of the system are reduced. This paper discusses the brief review of the SS-WPT, control strategy and implementation of the CV and CC control. Experimental hardware with 2kW output power has been performed and tested. The results show that the proposed CV and CC control method works well with the system.

1. Introduction
The concept of Wireless Power Transfer (WPT) had been introduced by Nikola Tesla more than one hundred years ago[1]. Nowadays, we can find various applications of the WPT from a small power such as biomedical applications[2] to a large power such as Electric Vehicles (EVs) charging system[3-5]. In term of power transfer application, there are two types of WPT technologies. Firstly, inductive coupling based WPT which is commonly called Inductive Power Transfer (IPT). Secondly, capacitive coupling based WPT which is called Capacitive Power Transfer (CPT). WPT system technologies contribute to safety and flexibility due to the cordless system. It is also more durable to the environment condition compared to a non-contactless system because it is not affected by dirt, dust, and chemical [6, 7]. A typical system of wireless charging for EVs, as shown in Fig. 1, consists of an AC-DC stage, inverter, compensator, coils, rectifier, and battery. The AC-DC stage serves either as the power factor corrector or a pre-regulator stage for the WPT system. It should be noted, in some cases, a post-regulator is added to control the output voltage and the output current of the WPT. However, in this paper, instead of adding a post-regulator stage, a variable frequency control is employed to regulate the output voltage and current. Since the WPT is used to charge the battery of the EVs, a Constant
Current (CC) and a Constant Voltage (CV) charging mode have to be applied to ensure the safety of the battery. This paper proposes the method to implement the CC and CV control for WPT. In this paper, we will discuss the brief fundamental theory of WPT, CC/CV control method, its realization, and the experimental results.

2. Characteristic of SS-WPT

IPT technologies employ the magnetic field to transfer the power from transmitter coil to the receiver coil. Since the transmitter and receiver coils separated with a relatively large gap, the coupling coefficient of the coupled coils is very low (0.1-0.3). At this condition, a direct power transferring is ineffective and inefficient. Many papers have introduced many types of the compensator to solve this problem. The basic types have been discussed in [8]. Series-series compensator is one of the basic compensator types that consists a capacitor connected in series with the coils in both sides of the WPT as shown in Fig. 2. Inverter stage converts the DC voltage ($V_{in(DC)}$) to a square wave AC voltage ($V_{in(AC)}$) with a magnitude gain $2\sqrt{2}/\pi$. The reversed process occurs in the rectifier stage, at which the magnitude gain of the output voltage ($V_o$) to the output AC voltage ($V_{out(AC)}$) is $\pi/2\sqrt{2}$. For this reason, the total magnitude of the SS WPT is determined by the compensator circuit as expressed in (1). A detailed analysis of SS WPT has been discussed in [9]. In (1) we can see the relationship of the voltage gain with the hardware parameters of compensator that includes the mutual inductance of the coil ($M$), self-inductance of transmitter side ($L_1$) and receiver side ($L_2$), compensator capacitors ($C_1$ and $C_2$), equivalent AC load ($R_{(AC)}$) and angular frequency ($\omega=2\pi f$). The output power ($P_o$) of the WPT is linear with the equivalent AC resistance of the system due to the relationship $P=V^2R^{-1}$. The plot of various output powers and mutual inductances are presented in Fig. 3. These plots based on these parameter: $L_1=432\mu H, L_2=442\mu H$ and $C_1=C_2=10\ \text{nF}$. The value of $M$ correspondent with the air gap distance between the transmitter and receiver coils such that $M=89.2\ \mu H$ is a representation of fully aligned coil with 200mm air gap.

![Figure 1](Typical inductive power transfer system for EVs.)

![Figure 2](Topology of a Series-series compensated WPT.)

![Figure 3](Voltage Gain Characteristic of SS WPT against load and mutual inductance.)
The characteristic of the SS-WPT can be seen in Fig 3. It’s clear that the voltage gain of the system depends on the operating frequency, mutual inductance, and load. However, there are conditions where the voltage gain of the system does not change against the variation of loads under the same mutual inductance. These marked frequencies with $\omega_{L1}$, $\omega_{L2}$, $\omega_{L3}$, and $\omega_{H1}$ are the independent load frequencies of the system under various mutual inductances. There are two independent load frequencies for each value of the mutual inductance. The first is on the left-hand side of the curve, and the second is on the right-hand side of the curve. We can see that if the mutual inductance decreases the first independent switching frequency (with L subscript) is decreased, and in contrary whenever the mutual inductance increases the second independent switching frequency (with H subscript) is increased. Selecting frequency at the independent load frequency is preferable because it provides a better efficiency of the system and reducing the effect of the variable load. However, because the voltage is controlled by using the variable frequency, there should be some consideration to applying this type of control. It will be discussed in the next section.

3. Control strategy of SS-WPT with CV and CC controller

3.1. Frequency selection

Practically, the mutual inductance of the coil is not constant at a fixed value. It always changes due to the misalignment and the air gap variation of the coupled coils. It results in a different independent load frequency of the system as shown in Fig 4. Because there are two independent load frequencies for each mutual inductance condition, the designers have to select the operating frequency region of the system. The frequencies $\omega_{L1}$, $\omega_{L2}$, and $\omega_{L3}$ are in the capacitive region of the system in which the realization of the Zero Current Switching (ZCS) is achievable. On the other side, $\omega_{H1}$, $\omega_{H2}$, and $\omega_{H3}$ are in the inductive region of the system. In this region, the Zero Voltage Switching (ZVS) can be achieved. If the ZVS is preferred rather than the ZCS, the frequency selection must be in the inductive region and vice versa. In this paper, the selected frequency range is in the inductive region. The range of the switching frequency should be selected carefully. Selecting frequency range too far from the resonant frequency generates more reactive power that results in lower efficiency due to the large conduction loss of the system. Fig 4 shows two examples of the frequency range selection. The Range I include the capacitive and the inductive region in one control mode. It can cause control failure due to the inconsistent behaviour of the voltage gain in the different region. Therefore, the frequency range should be limited to only one region for one control mode. For this case, selecting Range II is better compared to selecting Range I. The limitation of the minimum and maximum mutual inductance should be defined firstly to be able to select a more precise range of frequency. This mutual inductance limitation is related to the allowable misalignment and allowable air gap of the system. In this paper, the nominal resonant frequency of the system is selected to be 85 kHz, and the frequency range is 83 kHz to 91 kHz.

3.2. CV and CC controller

Fig 5 shows the typical charging steps of a Li-Ion battery [10]. Assuming the battery was initially at the low-level state of charge at which the battery voltage is lower than $V_{mb}$. In this state, the Equivalent Series Resistance (ESR) of the Li-Ion battery is large enough. Therefore the constant charging current is set to a lower
4. Implementation and Experimental Results

A prototype of SS-WPT with a hardware specification of $P_o=3$ kW has been developed. Both DC input voltage $V_{in(DC)}$ and the output DC voltage $(V_o)$ are 400 V. The MOSFET type and wireless communication module are FCH072N60F and nRF24L0+ single chip 2.4GHz transceiver respectively. The system has been tested under 2 kW output power with CV and CC control. The CC mode is configured to be activated at 5 A output current. The SS WPT system has been tested by using an electronic load configured in constant resistance mode. The testing result under the 2 kW output power condition is presented in Fig. 7. At this condition, the efficiency of the DC-DC stage achieved 97.9%. The CV and CC mode output voltage and current as shown in Fig. 8 shows that the CV mode is active when the current smaller than the setting current otherwise is CC mode. The transition from CV to CC mode and from CC to CV could perform well. A small spike occurs at the beginning of the CV

$$P_{out}(n) = K_p e(n) + i(n); \quad i(n) = k_i e(n) + i(n-1)$$

(3)
to CC transition because of the abrupt changing of output current and the controller need a little time to control.

![Voltage waveforms](image1)

![Current waveforms](image2)

**Figure 7.** Key-waveforms of SS-WPT.

**Figure 8.** Output voltage and output current at CV and CC operation.

### 5. Conclusion

A brief analysis and theory of the SS WPT and the implementation of the CV and CC control has been discussed in the previous sections. A hardware validation also has been successfully performed. We can conclude that the proposed technique can be used to implement the controller for wireless charging. Moreover, the hardware efficiency of the DC-DC stage could achieve 97.9% at full load condition with air gap 200mm.

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