Wireless Power Transfer in EVs

Sonu Koli (2022eeb1215@iitrpr.ac.in)

Introduction

"A problem is half done if you understand the question properly."

EVs are a sustainable replacement for fossil-based vehicles. Ongoing research and innovations have contributed to getting EVs worldwide recognition and implementation. However, EVs need further development as a newly introduced subject. This report focuses on how current charging methods of EVs work and how EV charging can be done using Wireless Power Transmission (WPT). But to understand all that, we need to understand the scope of improvement and why.

EV charging stations are limited, and one needs to go there specifically to get it charged. That, too, is a time-consuming process that causes discomfort to the user and thus acts as a considerable factor that hinders the mass adoption of EVs. Other reasons include continuous plugging and unplugging, which causes wear and tear to the charging equipment and plug. The installation cost and its overall impact on the power grid are also accountable issues.

EV Charging Methods

1. **Conduction Charging:** A plug-in port and a dedicated electrical outlet charge the EV battery. This method is further classified into types based on various definitions.

   a. **AC Charging (Level 1 and Level 2):** AC charging involves using a standard electrical outlet (Level 1) or a dedicated charging station (Level 2) to supply alternating current (AC) electricity to the vehicle's onboard charger. Level 1 charging is typically slower, while Level 2 offers faster charging rates due to higher power output.

   b. **DC Fast Charging (Level 3):** DC fast charging delivers direct current (DC) electricity at high power levels, enabling rapid charging of EV batteries. Level 3 charging stations are commonly found along highways and urban areas, offering convenience for long-distance travel and quick top-ups.

   c. **Smart Charging:** Smart charging uses advanced technologies and communication systems to optimize the charging process based on grid conditions, energy demand, and user preferences. Intelligent charging solutions may include demand response, time-of-use pricing, dynamic load management, and remote monitoring and control capabilities. Smart charging helps to reduce peak demand on the grid, maximize the use of renewable energy resources, and minimize charging costs for EV owners.

2. **Wireless Charging:** Wireless charging technology eliminates the need for physical cables and connectors by transferring power wirelessly from a charging pad or ground-mounted transmitter to a receiver installed on the vehicle. Broadly classified into:

   a. **Inductive Charging:** Inductive charging utilizes electromagnetic fields to transfer energy wirelessly between a charging pad or ground-mounted coil and a receiver coil installed on the vehicle. This technology eliminates the need for physical cables and connectors, offering EV owners greater convenience and ease of use. Inductive charging systems can be stationary or integrated into roads, parking spaces, and infrastructure.

   b. **Resonant Charging:** Resonant charging is a variation of inductive charging that uses resonance phenomena to achieve efficient power transfer over longer distances. This technology allows for greater flexibility in positioning the charging pad and receiver. It is well-suited for dynamic charging scenarios like moving EVs or parking in non-fixed positions.

Wireless Power Transmission

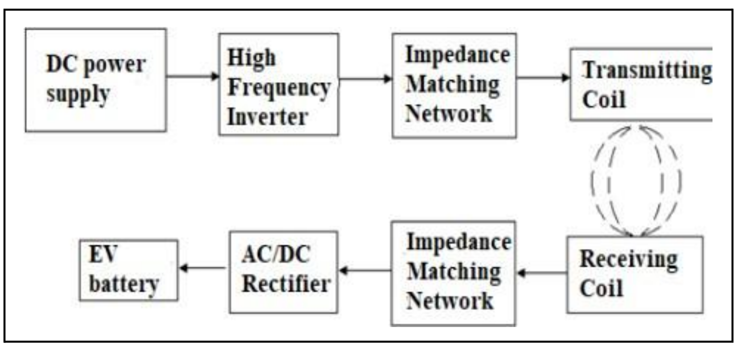
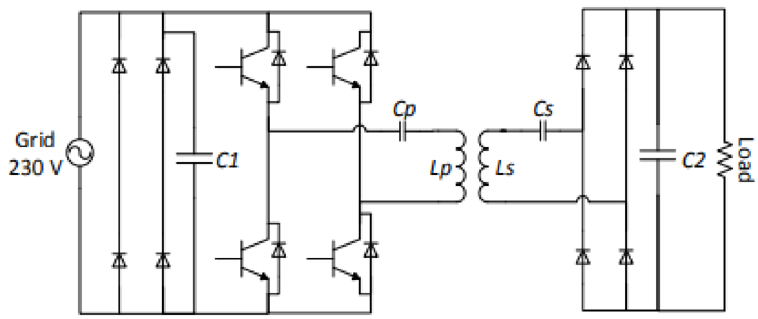


Fig: General Block Diagram for Wireless Power Transmission

Regarding power transfer in the air without wires and conductors, the Mutual Coupled Inductors are the most fundamental thought. When an electric current varies over time within a conductor, it generates a time-varying magnetic field around it. According to Faraday's Law, voltage will be induced across its terminals if a secondary loop is placed within this magnetic field when a load is connected to these terminals, completing the circuit, current flows, allowing power to be transmitted to the load. However, this setup is inefficient due to the exponential decrease in magnetic field intensity with distance.



Expected System Configuration

Power Electronics Converters:

1. **AC-DC Rectifier:** AC-to-DC rectifiers in EV charging systems are essential for converting grid AC power into DC, which is necessary for charging the vehicle's battery. They ensure efficient power transfer. Plugging in the EV initiates AC-to-DC conversion, followed by voltage and current regulation for safe and speedy charging. These rectifiers handle varying power levels and are adaptable to different charging settings, from home to public stations. Ongoing advancements aim to enhance efficiency, minimize heat, and support bidirectional power flow for V2G applications. Ultimately, these rectifiers are pivotal in driving EV adoption by offering dependable charging solutions.

2. **DC-AC Inverter:** DC/AC inverters are vital in electric vehicles (EVs) as they convert the stored direct current (DC) from the Rectifier into alternating current (AC) for wireless transmission of power through the coupled inductor for successful charging. This also plays a crucial role in modeling wireless charging systems for EVs, as this help efficiently transmit energy, contributing to performance, range, and sustainability.

3. **Mutually Coupled Inductor:** Transmits energy from the source side to the EV for charging. Most of this section is referenced from **[3]**.
   The system should operate at its resonance frequency to achieve optimal power transfer from the primary to the secondary. Capacitors Cp and Cs play a crucial role in attaining this resonance condition and compensating for losses in both the primary and secondary coils.
   $$\omega_0 = \frac{1}{\sqrt{L_p C_p}} = \frac{1}{\sqrt{L_s C_s}}$$ [**Condition for Resonance]**
   This can be simply achieved by setting: $L_p = L_s$, $C_p = C_s$

The coefficient of Coupling will be:

$$k = \frac{1}{[1 + 2^{2/3}(\frac{D}{\sqrt{R_1 R_2}})^2]^{3/2}}$$

Where D is the physical distance between the coils, for us, it is the distance between the charging platform and the EV. R1 is the radius of the coil in the charging platform, and R2 is the coil radius fitted in the EV. Adjusting k will ensure maximum power is transmitted from the platform to the EV battery charger.

The discussion about efficiency is concerning. This can be achieved by using various topologies available to use for study. The basic compensation topologies are Series-Series (SS), Series-Parallel (SP), Parallel Series (PS), and Parallel-Parallel (PP). (**Ref. [2]**)

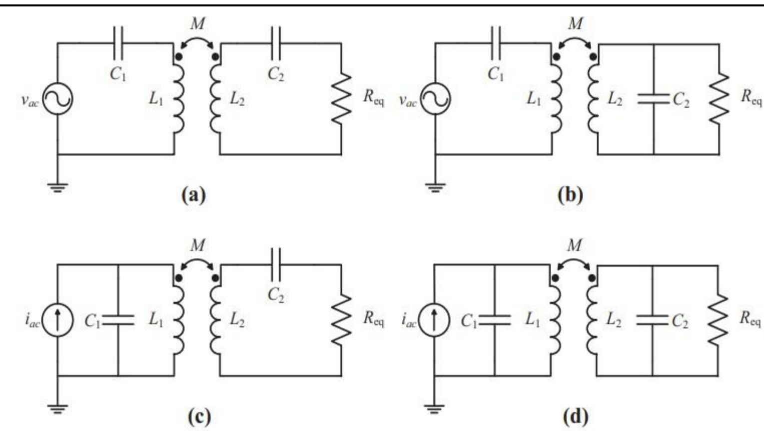


Fig. 5. Basic compensation topologies: (a) SS, (b) SP, (c) PS, and (d) PP. C_1, C_2 = capacitors; L_1, L_2 = coils; v_{ac} = alternating voltage; i_{ac} = alternating current; M = mutual inductance between the primary and secondary coils; R_{eq} = equivalent resistance.

I plan to discover and study more of these topologies and their current hybrids used during the internship period, such as LCC. (**Ref from [4] and [5]**)

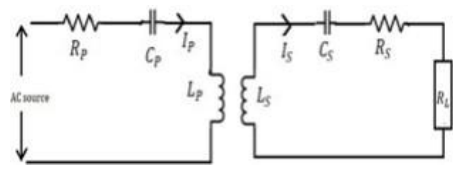


Figure to understand Power Transmission from Primary to Secondary

The calculations below theoretically help us understand how the circuit parameters can be adjusted to achieve maximum efficiency by ducting WPT for charging EVs.

KVL @ primary.

$$\boxed{V_p = I_p\left[R_p + j\omega L_p + \frac{1}{j\omega C_p}\right] - j\omega M I_s} \text{ --- (1)}$$

KVL @ secondory

$$\boxed{I_s\left(R_s + R_L + j\omega L_s + \frac{1}{j\omega C_s}\right) = j\omega M I_p} \text{ --- (2)}$$

from eq(1) and (2)

$$I_s = \frac{j\omega M V_p}{\left(R_p + j\omega L_p + \frac{1}{j\omega C_p}\right)\left(R_s + R_L + j\omega L_s + \frac{1}{j\omega C_s}\right) + (\omega^2 M^2)}$$

$$\boxed{I_s = \frac{j\omega_o M V_p}{Z_p(Z_s + R_L) + \omega_o^2 M^2}} \text{ --- (3)}$$

where

$$Z_p = R_p + j\omega_o L_p + \frac{1}{j\omega_o C_p}$$

$$Z_s = R_s + j\omega_o L_s + \frac{1}{j\omega_o C_s}$$

using resonance frequency $\omega_o = \frac{1}{\sqrt{L_s C_s}} = \frac{1}{\sqrt{L_p C_p}}$

$$I_s = j\frac{\omega_o M V_p}{R_p(R_s + R_L) + \omega_o^2 M^2} \text{ --- (4)}$$

As the calculations show, by applying simple KVL on both the primary and secondary sides of the system, one can quickly obtain the expressions necessary for the calculations of transmission efficiency.

efficiency $(\eta) = \frac{P_o}{P_i} = \frac{V_s I_s}{V_p I_p}$

$$\eta = \frac{(-j\omega_0 M \cancel{I_p})\left(\frac{j\omega_0 M \cancel{V_p}}{R_p(R_s+R_L)+\omega_0^2 M^2}\right)}{\cancel{V_p}\,\cancel{I_p}}$$

$$\eta = \frac{\omega_0^2 M^2}{R_p(R_s+R_L)+\omega_0^2 M^2}$$

$$\boxed{\eta = \frac{1}{\frac{R_p(R_s+R_L)}{\omega_0^2 M^2} + 1}}$$

Now writing eq in term of $Q_p = \frac{\omega_0 L_p}{R_p}$

$Q_s = \frac{\omega_0 L_s}{(R_s+R_L)}$ & $K = \frac{M}{\sqrt{L_1 L_2}}$

and we get $\boxed{\eta = \frac{K^2 Q_p Q_s}{K^2 Q_p Q_s + 1}}$

The higher value of $K^2 Q_p Q_s$ the higher efficiency can be achieved.

Here, $Quality\ Factor\ (Primary\ side)\ Q_p$, $Quality\ Factor\ (Secondary\ side)\ Q_s$

Efficiency (η) depends on $k^2 Q_p Q_s$ the higher the value of k and quality factors, the higher the theoretically expected efficiency of the system will be. (**Ref. [7] and [2]**) The above calculations have verified the same.

4. **Buck/ Boost Converter:** After the power is transferred to the secondary, one needs to either boost or buck it to attain a suitable output voltage for charging the battery. We must selectively choose the C, L, and Duty Ratio values per our requirement.

This here completes our theoretical modeling of the WPT for EV Charging stations. However, implementing this in real life comes with several challenges.

Challenges and Scope of Improvement:

According to the study, certain restrictions must be followed for the Wireless Charging of EVs. First, the whole concept of WPT is restricted by the idea of a mutually coupled inductor. The distance at which the manufacturer must fit the coil decides the D, and the type of coil used decides the R2. These two alone contribute to determining the mutual inductance M of the whole transmission. Hence affecting the efficiency and performance.
This means that there is a need to universalize the charging equipment used in EVs so that wireless charging stations are the same for everyone.

Next, we must consider these charging stations' overall impact on the grid. This can be managed by various techniques, such as monitoring the daily load curves and the idle time of the EVs when they are available for charging. Solar energy can also be used in these situations. Hence, this problem can be solved using various analyses and ML Techniques.

Case of Sweden's First EV Charging Road:
Sweden launched the first-ever EV charging Road that uses the Conduction Charging technique to charge vehicles as they glide on the road. Now, consider this done with the help of Wireless Transmission. The problem of exposed conductor strip wear and tear is caused by friction between the running vehicle and the road. Sweden's approach has paved the way for further advancements in EV charging methods. (Ref. [6])

When it Comes to innovations in EVs, the possibilities are limitless. This report briefly describes one type of wireless charging technique. We can also expand it to wireless charging in static/ dynamic state, Charging using Solar panels, and Charging using replaceable batteries, like using one battery and charging the other for future use. As told earlier, the possibility of research is limitless.

Bibliography

[1] An in-depth analysis of electric vehicle charging station infrastructure, policy implications, and future trends

[2] Wireless Power Transfer for Electric Vehicle Applications

[3] Design and Simulation of a Wireless Charging System for Electric Vehicles

[4] A review of wireless power transfer for electric vehicles: Prospects to enhance sustainable mobility

[5] Wireless Power Transfer in Electric Vehicles: A Review on Compensation Topologies, Coil Structures, and Safety Aspects

[6] Youtube: World's First Electric Road: Charging EVs While Driving

[7] Analysis of Wireless Power Transfer Technique for Electric Vehicle