Dynamic Wireless Charging for Electric Vehicles: Modeling and Efficiency Analysis

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Abstract— Electrical transportation systems necessitate the provision of various and efficient charging stations in order to promote the use of electric vehicles (EVs). With the advancement in technology, wireless power transfer has become a feasible alternative to conventional plug-in charging methods by providing convenience and efficiency. This paper introduces EV charging technologies along with the focus on wireless EV charging systems that would help achieve efficiency in power transfer. In this context, a comparative analysis between conductive and inductive chargers is provided in order to discuss the relative strengths and weaknesses of these charging technologies. In addition, dynamic wireless charging (DWC) has been presented as an effective means of charging that helps increase the power transfer efficiency and convenience by allowing EVs to be charged while in motion. DWC can provide solutions to the main barriers to the promotion of EVs such as limited driving range and time-consuming charging processes. The DWC systems have been modeled using resonant inductive power transfer technique where compensation network and resonance are used to improve efficiency. Simulation analysis was performed using MATLAB/Simulink and 90% efficiency was achieved under optimized conditions.

Keywords— Electric Vehicles, Wireless Charging, Dynamic Wireless Charging, Resonant Inductive Power Transfer, MATLAB/Simulink.

I. Introduction

Electric vehicles (EVs) are considered one of the most promising solutions for achieving better efficiency and lower carbon emissions within the transport domain. Nevertheless, their wide application is limited by such drawbacks as a relatively short drive range, extended charging period, and bulky battery packs.

Traditional conductive charging implies the use of connectors and entails time-consuming processes, thus compromising operational comfort and making EVs uncompetitive against regular cars that run on gasoline.

In order to address such challenges, wireless or inductive charging systems have emerged as contactless alternatives to traditional conductive plug-and-play systems. The advantages of wireless charging include better user-friendliness and access along with a decrease in mechanical wear and corrosion caused by connectors' exposure to the environment.

Moreover, there are no open connections in terms of electricity, hence greater safety when using the technology in outdoor conditions.

These features are well suited to the charging capabilities of lithium-ion batteries and could potentially contribute to improved battery lifetime, provided proper handling of temperature is implemented.

Although this technology is advantageous in many ways, it has some technological limitations that must be overcome in order to implement the system on a large scale, including low efficiency compared to conductive charging, sensitivity to the position of the coils, thermal stress to both power electronics and battery packs, low achievable charging power, higher cost, and electromagnetic compatibility issues.

Dynamic Wireless Charging (DWC) is an expansion of the wireless charging for stationary electric vehicles in which electric vehicles charge their batteries during movement with help of the power supplied from coils that are installed underground in the roadway. It helps to alleviate range anxiety and also minimizes the time needed for charging, allowing the use of smaller batteries.

By combining resonant compensation circuits, converters, and control techniques, DWC systems can provide a highly efficient power transfer. This paper examines a DWC system modeled with a resonant inductive power transfer approach analyzed in MATLAB/Simulink environment.

II. Literature Review

In recent times, much attention has been paid to wireless power transfer technologies for EVs through stationary inductive charging stations designed for use at home and public parking spots. Such systems offer better usability and reliability; nevertheless, they suffer from dependence on coil alignment as well as relatively low power transfer capability.

Various works were carried out to improve inductive coupling through the introduction of a resonant technique aimed at improving power transfer ratio and eliminating reactive power circulation within the compensating network.

An alternative solution can be provided by the dynamic wireless charging technique that allows energy delivery while the vehicle is in motion. Previous works have proposed segmented coils placed along the road, with selective activation of particular segments of the coil aimed at reducing stray magnetic flux.

Improved coupling techniques through the introduction of sophisticated control algorithms have been suggested to ensure that the device operates efficiently irrespective of alignment or load parameters.

Some of the major problems identified from previous studies include thermal management of the power electronic devices, electromagnetic interference, costly system design, and difficult implementation procedures.

Despite the promising simulation results indicating high efficiency rates, there is still a lack of experimental validation and standardization procedures.

III. System Components

The Dynamic Wireless Charging system includes a DC source, a high-frequency inverter, a primary compensation network, a transmitter coil, a receiver coil, a secondary compensation network, a rectifier, a DC-DC converter, a battery pack, and a control unit.

The DC source acts as a power input for the circuit, and its power is inverted to high-frequency AC using a power electronic inverter. High-frequency power is necessary because the highest energy transmission efficiency can be achieved in tens of kilohertz due to magnetic coupling.

The primary compensation network makes sure there is resonance in operation at this frequency to achieve highest efficiency of energy transmission.

The reception coil receives magnetic flux from the transmission coil and transforms it into electrical energy through electromagnetic induction.

The secondary compensation network sustains resonance and optimizes the coupling factor to allow the energy transfer to occur reliably even without proper alignment during movement of the vehicle.

The alternating current produced is then transformed into direct current with the help of a DC-DC converter before being charged into the lithium-ion battery pack with a CC–CV method of charging.

The controller constantly tracks voltage, current, temperature, and alignment conditions. Communication systems provide real-time interaction between the onboard control unit and the ground-side infrastructure.

IV. Block Diagram

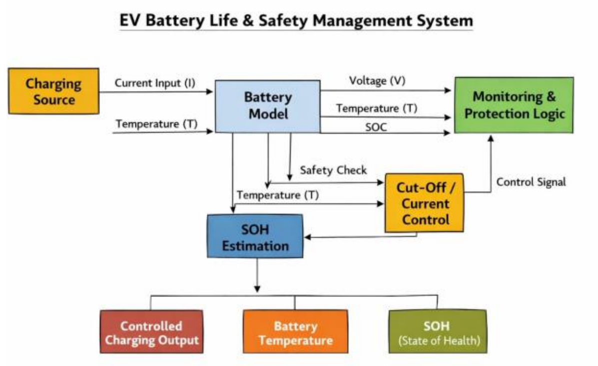

Figure 1: EV Battery Life and Safety Management System Block Diagram

The following are the main functions performed by the system: to charge the batteries safely; monitor the status of the battery; prevent damage that could result from aging, overvoltage, overcurrent, or overheating of the battery.

The system uses protective controls, battery modeling and monitoring, SOC/SOH estimation.

V. Methodology

A. Resonant Inductive Power Transfer

Wireless EV charging works on the principle of resonant inductive coupling, in which two coils resonate at the same frequency with the help of resonant capacitors. This phenomenon ensures maximum transfer of power through the air gap with minimum possible losses.

If the resonant frequencies of the two coils match, then the magnetic flux created by the transmitter coil will be optimally used by the receiver coil regardless of some level of misalignment.

The inclusion of resonant capacitors decreases the level of reactive power transferred by the inverter and increases the Q-factor. An improved Q-factor results in higher efficiency and stronger coupling of magnetic flux.

This technology can operate at very high frequencies ranging between 20 kHz to 100 kHz.

B. Power Flow Control and Regulation

The transferred power is controlled by manipulating the switching frequency, phase shift, or duty cycle of the inverter.

The closed-loop controller employs feedback from the receiver side to modulate the amount of transferred power based on different alignment and loading conditions.

Frequency shifting helps in operating the system slightly away from the resonant condition to either boost or suppress power transmission.

Phase shift is employed for precise power control at higher powers.

C. Battery Charging Strategy

The battery pack can be charged via a CC–CV algorithm.

In the initial stage of charging, constant current will be applied to provide quick changes in the state of charge.

When the battery voltage reaches the maximum level, the charging algorithm will shift to constant voltage to prevent overcharging.

The BMS monitors battery temperature, balance cells, resistance, and State of Health.

If thermal increase occurs, the control unit reduces charging current.

D. Alignment Tolerance and Efficiency Optimization

In order to counteract efficiency loss due to misalignment, frequency tuning techniques such as impedance matching are used.

When the vehicle travels across the charger surface, there is a significant change in the coupling coefficient.

Dynamic tuning based on feedback control tunes the resonant condition.

Segmented transmitter coils, active coil selection, and multiple frequencies help maximize magnetic field coverage.

E. Safety and Electromagnetic Compatibility

The detection of foreign objects and regulation of electromagnetic field guarantee adherence to safety guidelines.

Shielding structures minimize stray electromagnetic fields. International standards like SAE J2954 and ICNIRP are to be met.

Ferrite plates, aluminum sheets, and proper winding configuration of coils ensure magnetic fields remain contained. EMC filters assist in eliminating harmonic waves and inverter noise.

VI. Advantages

DWC provides multiple advantages compared to conductive charging methods.

Absence of physical connections increases convenience, minimizes wear, prevents corrosion, and decreases maintenance.

Contactless transfer increases electrical safety when exposed to moisture or dust.

Charging during movement helps reduce reliance on batteries and limits charging time.

Frequent charging while in motion is consistent with lithium-ion battery charging profile and may help improve battery lifetime.

VII. Challenges

Wireless energy transfer is less efficient than conductive charging owing to magnetic coupling losses, power electronics losses, and misalignment.

Thermal stresses on components and battery pack can accelerate lithium-ion degradation.

Wireless systems are limited in maximum power output compared to wired DC fast charging.

Performance strongly depends on coil alignment and air-gap variation.

Additional hardware requirements such as receiving coils, shields, converters, and resonant circuits increase total weight and cost.

VIII. Simulation Result and Analysis

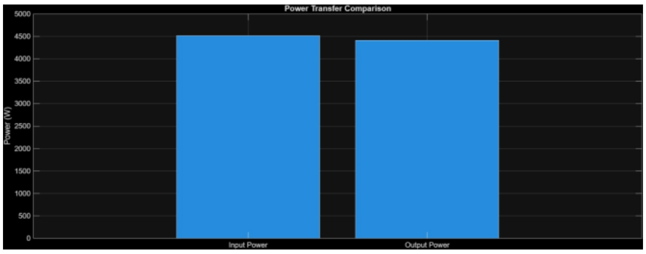

Figure 2: Efficiency vs Coupling Coefficient in DWC System

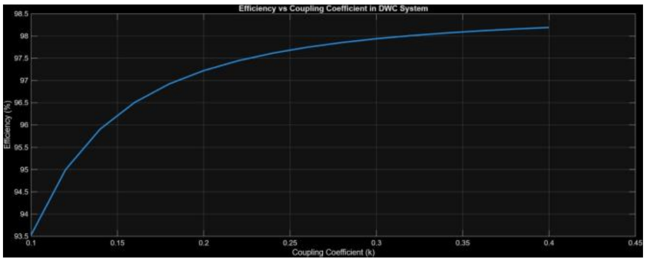

Figure 3: Power Transfer Comparison

The MATLAB simulation of the presented DWC system has helped gain insight into the behavior of power transfer and efficiency under dynamic operations.

From the power transfer results, the inverter uses 4.50 kW of input power while the receiver coil provides nearly 4.35 kW of output power to the load.

This shows negligible energy loss in the resonant inductive coupling system.

Different values of coupling factor were considered from 0.10 up to 0.40.

Efficiency gradually increased from about 93.5% at $k = 0.10$ to almost 98.2% at $k = 0.40$.

Since efficiency always remains above 90%, even under reduced coupling, the system shows high immunity to alignment errors.

These findings confirm the practical viability of the Dynamic Wireless Charging approach.

IX. Conclusion

This report provided an extensive discussion of wireless EV charging techniques, with emphasis on Dynamic Wireless Charging systems.

Benefits and drawbacks of wireless charging were examined, followed by methodologies concerning resonant inductive power transfer, power regulation, battery charging algorithms, alignment tolerance, and safety issues.

Simulation outcomes indicate that DWC has significant prospects in increasing charging ease and efficiency in electric vehicles.

Future research will be dedicated to experimentation, large-scale implementation, and optimizing control techniques under practical operational conditions.

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