Advanced Coil Design using ANSYS and Enhanced Converter Design for Dynamic Wireless Power Transfer in Electrical Vehicles

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Abstract: - A vehicle that powers on electricity rather than conventional fossil fuels like petrol or diesel is known as an electric vehicle, or EV. EVs can run on fuel cells that turn hydrogen into energy or on batteries that are charged by an external power source like a wall outlet or charging station. Battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs) are a few different forms of EVs. Compared to conventional cars, EVs provide a number of benefits, including cheaper running costs, lower pollutants, greater efficiency, and quieter operation. There are, however, significant difficulties, such as limited driving range, prolonged charging periods, and the requirement for charging infrastructure. Despite these obstacles, EVs are growing in acceptance and are anticipated to play a significant role in the switch to a more environmentally friendly transportation system.

Index-Terms: - Dual Active Bridge Converter (DAB), Dynamic Wireless Power Transfer System (DWPT), Dual Wireless Charging (DWC), Phase Shift Modulation (PSM).

I. INTRODUCYTION

The strict regulations regarding emissions, fuel efficiency, global warming, and limited energy resources, electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) have gained significant attention from automakers, governments, and consumers alike. To develop cost-effective and reliable EVs and PHEVs, research and development efforts have largely focused on advancements in battery technology, charging infrastructure, and motor and drive systems. Among these, charging infrastructure plays a critical role in ensuring the effective operation of EV/PHEV systems. The primary challenge in the widespread adoption and commercialization of EVs lies in battery-related issues. These batteries are often heavy, bulky, costly, and have a limited lifespan. Additionally, the need for frequent charging and the short driving range due to low energy density are significant barriers to EV development on a global scale. One potential solution to address these battery challenges is Dynamic Wireless Power Transfer (DWPT). This system allows EV batteries to charge while the vehicle is in motion. In such a setup, transmitter coils are embedded in the road, and a receiver coil is mounted beneath the vehicle. With a well-established charging infrastructure capable of charging vehicles as they drive, the size of onboard batteries can be reduced, and the driving range of EVs can be extended.

This Paper presents an in-depth study of dynamic wireless charging (DWC) systems, focusing on the design and comparison of various coil shapes, sizes, and winding patterns. It offers a comprehensive analysis and modelling of different coil structures for DWC systems, with performance evaluation through simulations of mutual inductance, coupling coefficient, magnetic flux, and magnetic field distribution. The work also addresses the issue of misalignment in DWC systems. Using computer-assisted simulation software, ANSYS MAXWELL 3D, a 3D analytical model of various coils is presented. To support different misalignment scenarios, the paper illustrates simulation outcomes such as coupling coefficient, flux linkage, magnetic flux density, and mutual inductance, all in response to variations in axis parameters. Furthermore, the study explores the power converter system used in dynamic wireless charging applications.

Additionally, a state-space model for a dynamic wireless power transfer (DWPT) system is proposed. The DWPT system consists of emitter coils powered by AC/DC and DC/AC converters, with phase angle control to maximize power transfer. The receiver coil is connected to a full-bridge diode rectifier and an equivalent load resistance. To simulate the dynamic movement of wireless power transfer, the coupling

factors between the emitter and receiver coils are set to vary based on the receiver's movement relative to the emitter coils. This control strategy successfully achieves maximum power transfer under changing coupling coefficients, ensuring stable power and voltage across the load during transient states. The primary objective of this research is to design and optimize various coil structures for dynamic wireless charging (DWC) systems, comparing different shapes, sizes, and winding patterns to maximize power transfer efficiency. This involves developing comprehensive models using ANSYS MAXWELL 3D to simulate key performance metrics such as mutual inductance, coupling coefficient, magnetic flux, and field distribution. Additionally, the study aims to address the impact of coil misalignment on system performance and propose solutions to mitigate its effects. A nonlinear state-space model for dynamic wireless power transfer (DWPT) systems will also be developed, incorporating variable coupling factors.
due to dynamic movement to ensure optimal power transfer. The research further explores the performance of power converter systems in DWC applications, ensuring stable power delivery during transient states. Extensive simulations will be conducted to validate the system's performance under various conditions, contributing to the advancement of efficient and reliable EV charging technology.

II. DYNAMIC WIRELESS CHARGING SYSTEM

Dynamic wireless charging (DWC) is a revolutionary technology that aims to power electric vehicles (EVs) while they are in motion. It works by embedding transmitters in the road surface that generate a magnetic field. Vehicles equipped with receiver coils installed underneath capture this magnetic field and convert it into usable electrical energy to charge the battery. This eliminates the need for physical plugs and cables, offering a convenient and seamless charging experience. DWC has the potential to significantly enhance the range of EVs, reduce infrastructure costs, and contribute to a more sustainable future of transportation.

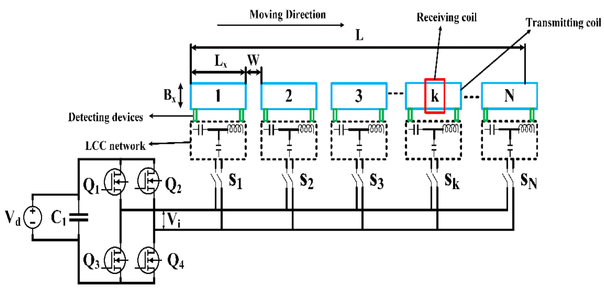


Fig.1: Dynamic wireless charging (DWC) system.

In the Fig.1, a single receiving coil denoted by k is placed on the vehicle, indicated by the periphery. The LCC compensation network is utilized to compensate for the reactive components of a single transmitting coil. N switches (S_1, S_2...S_N) are connected to the LCC networks and high-frequency inverters to adjust the power supplied to the coils. A single receiving coil, represented by k in Fig.1, is mounted on the vehicle, which is depicted by the perimeter. The reactive parts of a single transmitting coil are taken into account by the LCC compensation network. To modify the power provided to the coils, N switches (S_1, S_2...S_N) are linked to the high-frequency inverters and LCC networks.

A. *Operation Of DWC*

The operation of the dynamic wireless charging system has a switches sw_1 and sw_2 as a shown in Fig.2. regulate the activation of the transmitting coils, which are coupled to the HFI (high frequency inverter). There are three steps to the segmented DWC system's functioning, which are broken down as follows.
STAGE 1: sw_1=ON, sw_2=OFF
STAGE 2: sw_1=ON, sw_2=ON
STAGE 3: sw_1=OFF, sw_2=ON

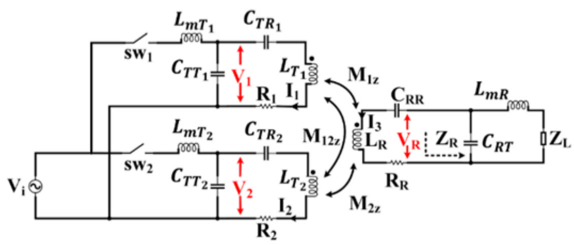


Fig.2: Circuit diagram of the DWC system.

In this study, an optimized setup with two transmitting coils (T_x) and one receiving coil (R_x) is taken into account. Fig.2 circuit schematic serves as an example of the configuration. The formula below may be used to calculate the different values of the LCC network.

$$L_{mT\_n} = \frac{X_T}{\omega} \quad (1)$$

$$C_{TT\_n} = \frac{1}{\frac{\omega}{X_T}} \quad (2)$$

$$C_{TR\_n} = \frac{1}{\frac{\omega}{(\omega L_{T\_n} - X_T)}} \quad (3)$$

The expression for X_T can be given as follows.

$$X_T = \frac{V_i}{I_n} \quad (4)$$

B. *Coupling Pads*

In order for the DWC (Dual Wireless Charging) technology to work, coupling pads are essential. These pads must have particular properties, such as a high-quality factor (Q), high tolerance for misalignment, and a high coupling coefficient (k). For the DWC system to operate as effectively and efficiently as possible, certain characteristics are essential. The parameters mentioned above are influenced by the shape of the inductor, the core material used, and the spacing between the coils (i.e., the transmitting and receiving coils). In a DWC system, the efficiency of linked inductors is determined by the quality factor and magnetic coupling coefficient of the inductor. The geometric average of the quality factors of the transmitter and receiver, denoted as Q, can be expressed as follows:

$$Q = \sqrt{Q_T Q_R} \quad (5)$$

$$Q_T = \frac{\omega L_T}{R_T} \quad (6)$$

$$Q_R = \frac{\omega L_R}{R_R} \quad (7)$$

C. *Coil Misalignment*

Wireless coil misalignment significantly impacts the efficiency of wireless power transfer systems, including those used for dynamic wireless charging of electric vehicles. When the transmitter and receiver coils are not perfectly aligned, the magnetic coupling between them weakens, reducing the amount of power that can be transferred. This can lead to decreased charging speed, reduced vehicle range, and potential system instability**.** The various kinds of misalignment that may occur in the system are depicted in Fig.3. Based on the various locations of the receiving (R_x) coil, these misalignments are divided into several categories.

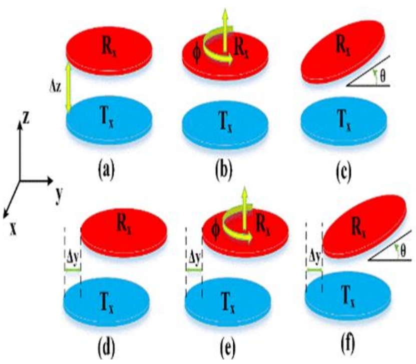


Fig. 3. Various types of misalignments (a) vertical, (b) planar, (c) angular, (d) longitudinal, (e) planar and longitudinal, and (f) angular and longitudinal.

III. DUAL ACTIVE BRIDGE CONVERTER

A Dual Active Bridge (DAB) converter is a type of power electronic converter that allows for efficient and bidirectional power transfer between two DC voltage sources. It uses two H-bridge circuits connected by a high-frequency transformer to enable this power flow. By precisely controlling the phase shift between the two bridges, the direction and magnitude of power transfer can be regulated. This makes DAB converters suitable for various applications like renewable energy systems, electric vehicles, and battery energy storage systems.

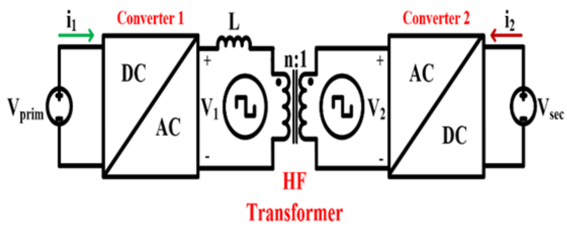


Figure.4: Basic diagram of DAB converter.

The DAB converter, as implied by its name, consists of two active bridges, which are the same as the controlled complete bridges. Two complimentary high-frequency square waves produced by these bridges can be phase-shifted with respect to one another. The switching frequency of the two complete bridges, also known as the switching frequency, determines the frequency of these AC signals. The two high-frequency square waves in this system, V_1 and V_2, are represented by their respective voltages in this system by the two DC buses, Vprim and Vsec. The voltage and current passing through the inductor are extremely important in controlling the power flow inside the converter. The value of the transformer's leakage inductance and any external series inductance is represented by the symbol L, which stands for inductance. The basic principle is that by using square waves to the bridges, a voltage differential is produced across the energy transfer inductance, guiding the flow of stored energy.

A. *Single Phase Shift Modulation*

The DAB converter has a simple topology, but due to the huge number of controlled switches, a method must be developed to manage the phase shift ratio between the two square waves and, consequently, the converter's power flow. Phase shift modulation (PSM) approaches use the phase shift of the two AC signals to transfer power and modify voltage levels. Therefore, the goals of the modulation approaches are to reduce power losses while ensuring a consistent output signal.

The SPS modulation method, which is well-known for being straightforward and widely used, is frequently used by the DAB converter. In this method, two complementary square waves are used, each with a fixed 50% duty cycle and a fixed switching frequency. The largest power flow that may be achieved is provided through SPS modulation. It does have two significant flaws, though. First of all, it causes a greater RMS transformer current, which increases conduction losses. Second, the operational range in which zero voltage switching can be used is constrained. However, SPS modulation is selected for this praper because to its simple implementation.

$$P_{2,sine} = \frac{V_1 V_2}{2\pi^2 f_{sw} L}\delta(\pi - \delta) \qquad -\frac{\pi}{2} \le \delta \le \frac{\pi}{2} \tag{8}$$

B. *State Space Analysis*

The state space analysis of a dual active bridge converter shown in Fig. 5 provides insightful information about how it operates, aiding system modelling, simulation, stability analysis, control design, and performance optimization. A complete knowledge of the converter's operation can be attained by describing the dynamic behavior of the converter using a collection of state space equations, which are a type of first-order differential equation. These equations are derived from basic circuit principles, such as Kirchhoff's voltage and current laws and equations guiding the switching behavior of the converter.

Case I: this case, the Switch 1 and Switch 4 of the primary side of the transformer are closed thereby giving the polarity of the transformer. The current flow orientation of i_C across the capacitor is from B to A

Case II: This case, the Switch 2 and Switch 3 of the primary side of the transformer are closed. The polarity of the transformer in this case is the reverse of that of the case 1. Therefore, the current flow orientation of i_C across the capacitor is from A to B.

Case III: This case, the Switch Q1 and switch Q4 of the secondary side are closed. Where the current direction across the inductor and the capacitor

Case IV: the Switch Q2 and switch Q3 of the secondary side are closed. where the current direction across the inductor and the capacitor.

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L_1} \\ \frac{1}{C} & \frac{1}{RC} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{V_2}{L_1} \\ 0 \end{bmatrix} \tag{9}$$

The efficiency for the DAB is given by,

$$\eta = \left[\frac{P}{P + P_{DAB(loss)}}\right] \times 100\% \tag{10}$$

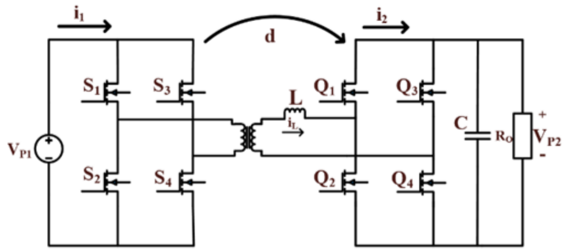


Fig.5: Basic structure of DAB converter

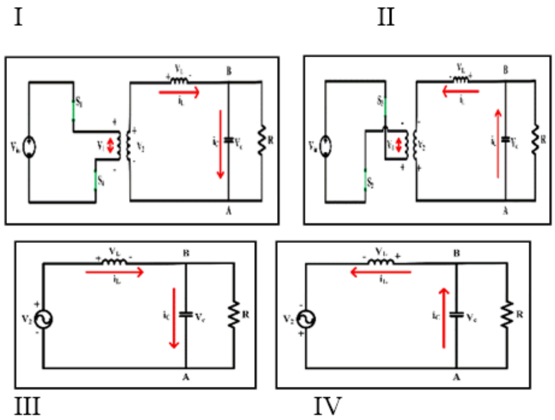


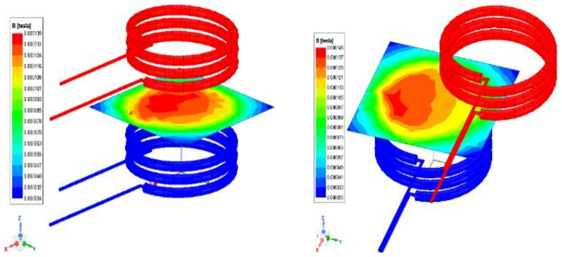
Fig.6: Equivalent circuit of 4 cases

IV. RESULTS AND DISCUSSION

This section presents the simulation and analysis results of the proposed DAB converter. The circuit-level performance, including power transfer efficiency, voltage gain, and dynamic response, is evaluated using MATLAB Simulink simulations. To assess the electromagnetic characteristics of the wireless power transfer coil, detailed finite element analysis (FEA) is performed using ANSYS Maxwell 3D. By combining these simulation tools, a comprehensive understanding of the converter's overall performance is achieved.

A. *Vertical and Longitudinal Misalignment*

The simulation studies carried out in this research concentrate on the investigation of a dynamic wireless charging (DWC) system, particularly looking into the misalignment between a single transmitter coil and a single receiver coil. Utilizing ANSYS MAXWELL 3D, the suggested analytical model is validated. In order to replicate the transmitter (Tx) and reception (Rx) coils, an air gap spacing of 44 mm along the



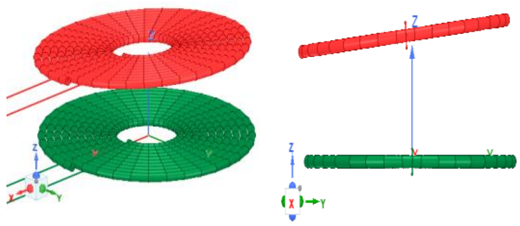
(a) (b)

Figure.6: Magnetic field density between Tx and Rx with the variation of (a) 0 mm y-axis and 44 mm z-axis. (b) 40 mm y-axis and 44 mm z-axis.

vertical z-axis was used. However, two situations are taken into account for the longitudinal y-axis: one with no misalignment (distance of 0 mm) and the other with a 40 mm misalignment.

B. *Angular, Vertical and Longitudinal - Misalignments*

The transmitter coil (Tx) was energised with a 4A current in order to conduct an analytical analysis of the system, while the reception coil (Rx) was left without power. To learn more about their effects on the dynamic wireless charging (DWC) system, several misalignments were made. These misalignments ranged from 0 mm (perfectly centred) up to 100 mm (the maximum longitudinal misalignment between the receiver and transmitter coils), as well as angle deviations of 4° and 10°. Evaluation of the DWC system's performance in various misalignment circumstances was the goal. Circular, rectangular, and hexagonal spiral coils inner diameter and number of turns were held constant throughout the investigation to guarantee a fair comparison. Insights into the system's performance and its capacity to sustain effective power transmission despite the imposed deviations were obtained by systematically studying these misalignments.



(a) (b)

Fig.7: Model structure of circular spiral coil for 4° deviated angle in the x-axis, (a) Dimetric view of the circular spiral coil with 100mm air-gap and (b) front view of the circular spiral coil with 100mm air-gap.

C. *Magnetostatic Setup in Ansys Maxwell 3D*

To evaluate the electromagnetic performance of the WPT coil, a detailed magnetostatic analysis was conducted using ANSYS Maxwell 3D. The 3D model of the coil, including the core material and surrounding air, was accurately defined. Appropriate boundary conditions and meshing techniques were employed to ensure accurate simulation results. The simulation results provided insights into the magnetic field distribution, inductance, and efficiency of the coil. Additionally, a sensitivity analysis was performed to investigate the impact of design parameters on the coil's performance.

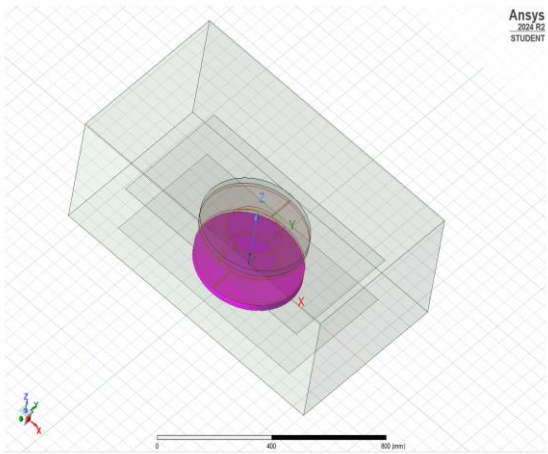


Fig 8. A View of Complete model WPT, here the air is shown by the 3D box.

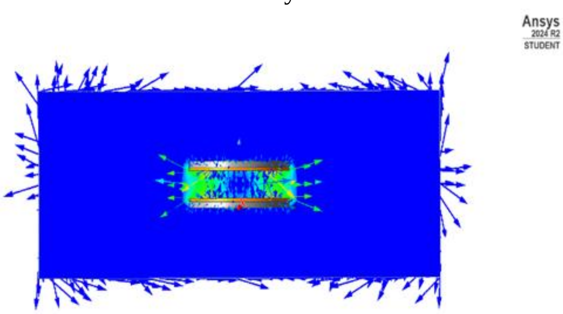


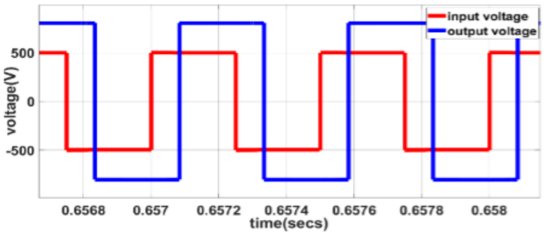
Fig.9: Field Overlays of WPT System

D. *Simulink Results*

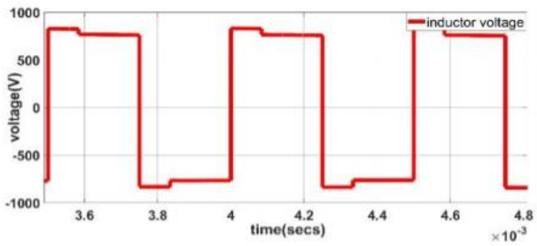
The DAB converter topology of both the phase shift and without phase shift model is designed using the parameters given in Table.1. The input voltage supplied to the high frequency transformer is taken as 500 volts, the output voltage given out on the secondary side of the high-frequency transformer is taken as 800 volts, the inductance and the capacitance values are considered to be 2.5 mH and 1000 μF respectively and lastly, the switching frequency is considered as 20 kHz. The simulation of the designed DAB converter topology is performed using the Simulink platform of the MATLAB version R2023a.

Table.1: Parameters of DAB converter

PARAMETERS	VALUES
Input Voltage, V_S	500V
Output Voltage, V_O	800V
Inductance, L	2.5mH
Capacitor, C	1000µF
Switching frequency, f_s	20kHz



(a)



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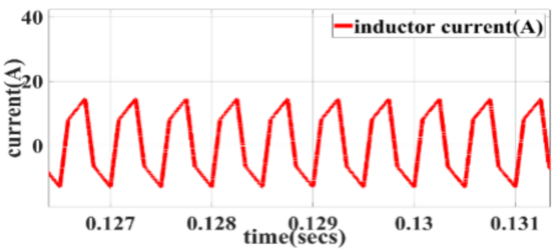
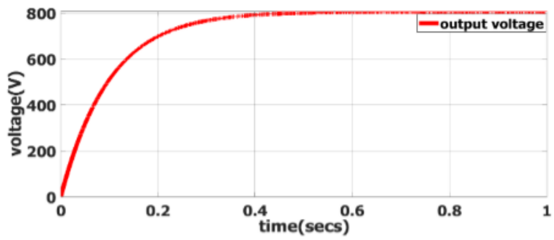
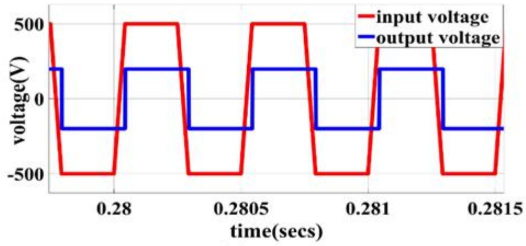


(c)

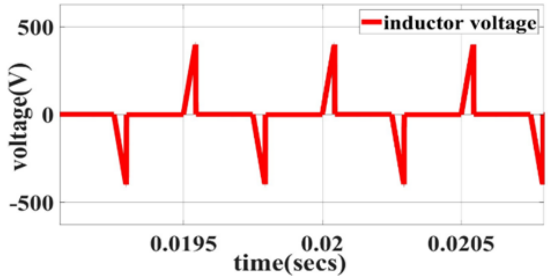


(d)

Fig.10: DAB for Boost mode of operation (a) Input and output voltage of high frequency transformer (b) Inductor voltage (c) Inductor current (d) Output voltage



(a)



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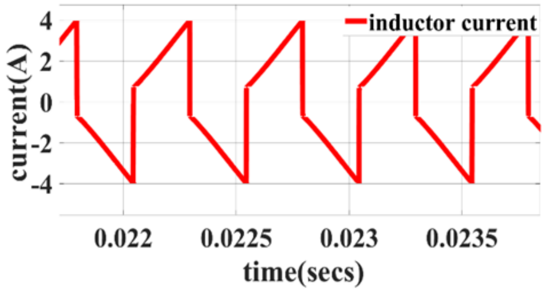
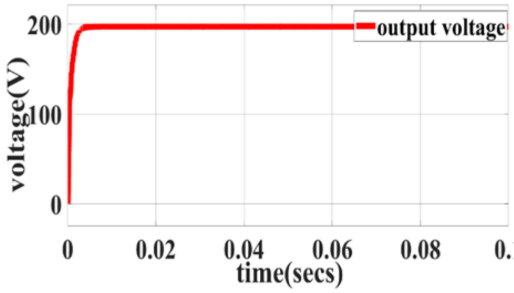
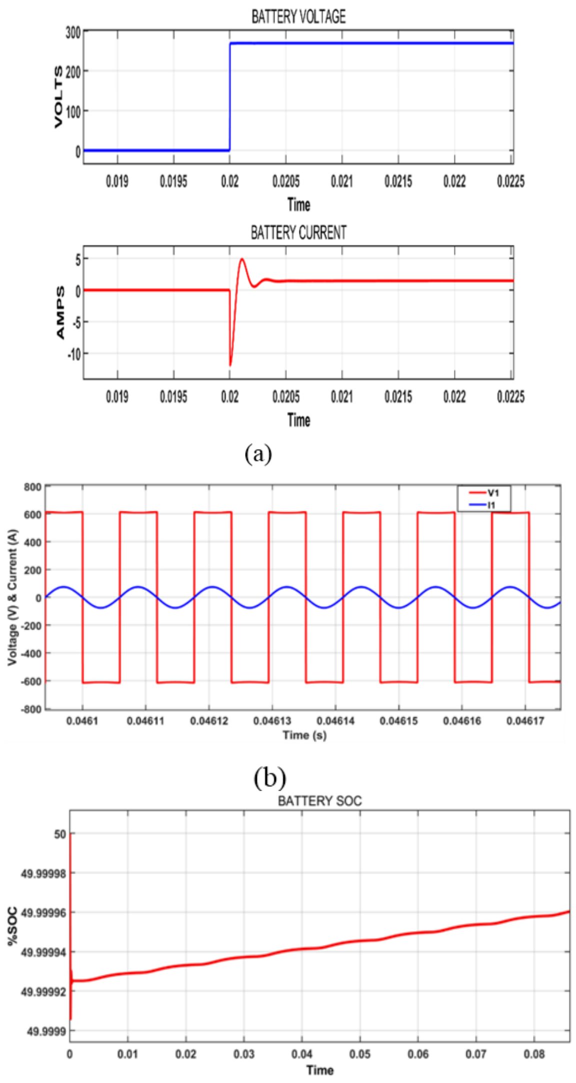


(c)



(d)

Fig.11:. DAB for Buck mode of operation (a) input and output voltage of high frequency transformer (b) inductor voltage (c) Inductor current (d) output voltage



(c)

Fig.12: The simulation results of the CLLC-type symmetric resonant DAB converter. (a): shows the battery voltage of around 250V and charging current of 2 amps. The state of charge (SOC) of the battery is indicated in (b). the Input voltage and current output of the transmitting coil is shown in (c).

CONCLUSION

This research presents a comprehensive investigation into the design and performance optimization of coil structures and power converters for dynamic wireless charging systems. The primary objective is to enhance the efficiency and reliability of wireless charging, particularly in scenarios involving device movement. A thorough analysis of various coil topologies was conducted to optimize power transfer, magnetic field distribution, and mutual inductance. Mathematical modeling and simulations were employed to accurately predict the impact of misalignment on system performance. Additionally, a single-phase dual active bridge (DAB) converter was investigated in detail, considering factors such as operating modes, power loss mechanisms, and efficiency optimization. By understanding these key components and their interactions, this research contributes to the advancement of wireless power transfer technology. The insights gained from this study can be applied to the design of more efficient and robust wireless charging systems, laying the groundwork for a future where wireless power transfer is commonplace. This research not only addresses the technical challenges associated with dynamic wireless charging but also provides practical guidelines for the development of real-world applications.

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