

Design of Wireless Charging System for Electric Vehicle Using Sliding Mode Controller

Basma Abdullah Abbas^{a,1,*}, Hosham Salim Anead^{a,2}, Khalid Faisal Sultan^{a,3}

^a Electromechanical Engineering Collage, University of Technology, Baghdad, Iraq

¹ basma.a.abass@uotechnology.edu.iq; ² 50043@uotechnology.edu.iq; ³ 50084@uotechnology.edu.iq

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ABSTRACT

This research focused on using a sliding mode controller and resonant inductive wireless charging system to improve electric vehicle charging. Wireless charging in electric vehicle has significant challenges in terms of charging time and operating battery efficiency. The main contribution this work is control the battery charging via sliding mode controller by constant voltage constant current technique based on proposed design. Initially, the system was designed by simulation program and consisted of the transmitted side which included grid, three phase rectifier, DC-DC boost converter, and DC-AC high frequency inverter, mutual inductance (one coil transmitter and six coil receiver), and receiver side (single-phase rectifier and battery pack). To achieve level 3 DC fast charging, a sliding mode controller was used to regulate the current and voltage by selecting appropriate number of coils in receiving side to fix at 100 A and 800 V, respectively. The simulation design and control were simulated using MATLAB 2022b. As a consequence, the DC-DC boost converter increased the transmitted voltage to 800 V within 20 KHz to minimize wave signal ripple, while a sliding mode controller maintained the transfer voltage and constant current at 800 V and 100 A, respectively, throughout charging from 10% to 100%. Furthermore, a sliding mode controller operated to charge the system within 25 minutes as a fast-charging method. Finally, the behavior and value of the voltage that delivered to the battery have been confirmed.

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1. Introduction

The number of electric vehicles (EVs) has increased fast as a result of lower CO₂ emissions and the fact that energy is significantly cheaper than gasoline. As a consequence, there is a need for constant improvements to charging infrastructure, especially wireless infrastructure, which must be compatible with both public and home charging stations and designed for private, commercial, and public usage [1], [2]. Wireless power transmission technology avoids the need for cables, making electronic devices more portable, convenient and safe for all users compared to cable connections. Thus, the availability of wireless charging stations overcomes the concerns of charger connection, charging time and range anxiety-possibly the most significant impediments to the widespread usage of EVs [3]. The four wireless power transmission (WPT) strategies are inductive wireless charging system (IWCS), capacitive wireless charging system (CWCS), resonant inductive wireless charging

system (RIWC) and permanent magnetic gear wireless charging system (PMWC). From the several WPT methods, capacitive and inductive techniques have the most practical uses. The most often utilized techniques are IPT and RIWC, which operate with a wide range of power outputs and gap widths. Furthermore, IPT may be used for huge air gaps of several meters and has much higher output power than CPT. CPT is just acceptable for power transmission with naturally short gap lengths due to voltage constraints, and it is only useful for low-power applications with very small air gaps ranging from 10 to 4 m [4], [5]. Microwaves, on the other hand, can transport electricity across long distances with high output power while operating at frequencies ranging from 1 GHz to 1000 GHz. This technology is costly and dangerous to people [6], [7]. Compensation circuits including an inductor and a capacitor should be considered when applying WPT via IPT. There are four types of fundamental compensation topologies: Series-Series (SS), Series-Parallel (SP), Parallel-Parallel (PP), and Parallel-Series (PS) [8], [9].

In terms of power transfer efficiency and maximum output power, the SS- topology outperformed the SP- topology, which maintains high efficiency throughout the WPT process but is affected by fluctuations in resonance frequency and coupling coefficient [10]. SMC has exceptional resilience to model mistakes, parameter fluctuations, and external disturbances, prevalent in electric vehicle applications such as motor control, braking, and steering. This durability guarantees dependable operation despite fluctuating road conditions, load variations, and system nonlinearities [11]-[13]. A number of researchers have employed the sliding mode controller in electric cars, where [14] has been used several types of controllers to manage the output voltage from the buck converter to the battery for charging purposes. One controller was a Proportional-Integral (PI) controller, while the other was a sliding mode controller. They used pole-zero plot and Bode plot methodologies for evaluating system performance. This model was designed for electric vehicle charging stations under dynamic load situations. The SMC demonstrated superior performance relative to the PI controller, characterized by reduced ripple, an accelerated settling time, and absence of peak overshoot. Also Designed a direct current microgrid including solar photovoltaic arrays and a level 3 electric vehicle fast charging system (EVFCS) by [15].

Two control methodologies for rapid electric vehicle charging were fuzzy logic and sliding mode controllers. The controllers used to evaluate the system's performance implement a constant current (CC) method to control the current output of the electric car charger. The findings indicated that the SMC exhibited superior performance relative to the FLC regarding the decrease of voltage overshoot and initial peak current of the EV battery, while sustaining a stable fast-charging current. Another studies have focused on battery conservation techniques based on the concepts of constant voltage, constant current, or both, using control theories such as proportional integral (PI), fuzzy logic, neural networks and adaptive neuro fuzzy (ANFIS) controllers. These ideas may be utilized to regulate either the main or secondary voltage and current. It was the most successful because it employed nonlinear control theories to regulate both voltage and current concurrently [16]-[20].

Finally, the power transfer operation reached about 6.6 KW to 50 KW in 30 minutes by connecting compensating circuits (SS and SP) using IWCS and RIWC approaches. Researchers continue to investigate various methods to increase the efficiency of charging batteries more rapidly by boosting the transmitted power [21]-[24]. On the other hand, choosing suitable coils for EV wireless charging is essential for enhancing efficiency, dependability, and adaptation to practical settings. MATLAB and associated simulation tools are extensively used to model, optimize, and verify coil designs, taking into account aspects like as geometry, compensation topology, misalignment, and power transfer efficiency [25]. An electric vehicle compact multi-receiver system employing inductive power transfer (IPT) presented by [26]. MATLAB and ANSYS Maxwell simulations analyze coil misalignment-induced dynamic mutual inductance effects on power output and efficiency. The findings demonstrated optimum power transfer at the resonance frequency and 92% efficiency, suggesting efficient power transmission in moving vehicles. A dynamic wireless power transfer (WPT) method for electric vehicles (EVs) using two receiver coils was built and simulated in MATLAB 2021a by [27]. The suggested technology improves power transmission and efficiency during dynamic charging situations like highway driving or automatic parking, when

transmitter and receiver coils are misaligned. A VEENA Rectifier-based architecture is used, with an AC supply, HF inverter, resonant inductive connection with two receiver coils, rectifier, and battery. Two receiver coils maximize power capture and lateral misalignment tolerance. The MATLAB 2021a simulation results show that the suggested technique achieves steady and efficient power transfer during dynamic charging. System performance is measured by power transfer efficiency, output power, and misalignment tolerance. The dynamic WPT system with two receiver coils has the potential to be used in EV charging infrastructure, advancing wireless charging technology.

Current work, SMC was used to regulate a current and voltage simultaneously. Whereas the proposed design depends on the number of secondary coils which selected by SMC with employing series-series topology as a main contribution. This research covers the essential concept of WCS, the charging of electric cars and a mathematical model. Section 2 discusses the equation and mathematical model of wireless charging. Section 3 present the methodology of sliding mode controller. the final Section explain the results and discussions.

2. Wireless Charging

This section deals with wireless power transmission work principle in addition to present the mathematical equation for wireless power transmission.

2.1. Wireless Charging System for EV Charging

According to the wireless charging system, air gaps, size, shape, and material should all be considered to enhance power transmission [28]. Fig. 1 explains how to charge an electric vehicle's battery from the grid. The charging process from grid to battery is divided into four steps: using a rectifier to convert the voltage from AC to DC, using an inverter to convert the DC to AC with high frequency, and using mutual inductance to transfer the power. Finally using a single-phase rectifier to convert the voltage from AC to DC that supply to battery [29]-[32].

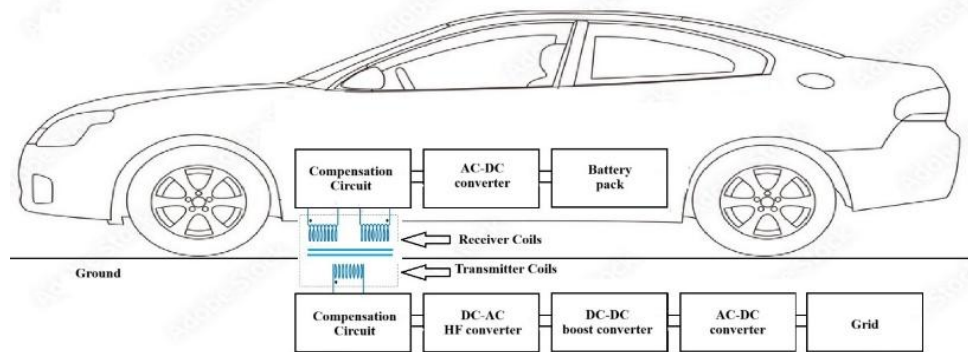


Fig. 1. Wireless power transmission technology for electric vehicles

2.2. Mathematical Model of WPT

The four compensation topologies used in the transmitting and receiving circuits of wireless power transmission system are Series-Series (S-S), Parallel-Parallel (P-P), Parallel-Series (P-S) and Series-Parallel (S-P). The WPT equivalent circuit model is based on the coil's compensating capacitor positions [33]-[36]. Fig. 2 depicts the identical circuit for the WPT system, which has a single transmitting coil and several receiving coils.

The supplied circuit is theoretically described by Kirchhoff's voltage law. This is one way to represent the voltage that passes through the transmitting coil [8]:

$$V_s = \left(R_1 + j\omega_0 L_1 + \frac{1}{j\omega_0 c_1} \right) I_1 + j\omega_0 M I_2 \quad (1)$$

Where, the mutual inductance is M , supply voltage is V_s , primary and secondary currents are I_1 and I_2 respectively, primary resistance, inductance, capacitance are R_1 , L_1 and c_1 respectively and angular frequency is ω_0 . When Kirchoff's law is applied to the circuit's receiver side, it produces:

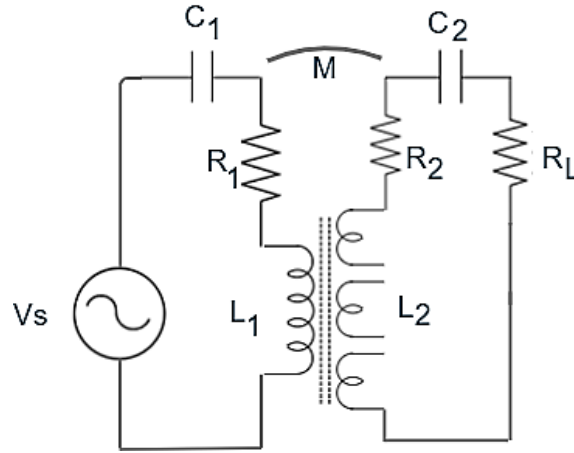


Fig. 2. WPT system circuit

$$0 = \left(R_2 + j\omega_0 L_2 + \frac{1}{j\omega_0 c_2} \right) I_2 + j\omega_0 M I_1 \quad (2)$$

Where, the secondary resistance, inductance, and capacitance are indicated as R_2 , L_2 and c_2 respectively. Eq. (1) and “Eq. (2)” may be expressed using the matrix shown:

$$\begin{bmatrix} Z_1 & Z_m \\ Z_m & Z_2 + Z_L \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} V_s \\ 0 \end{bmatrix} \quad (3)$$

The coefficients of the load impedance (Z_L), mutual impedance (Z_m), primary coil impedance (Z_1) and secondary coil (Z_2) are represented according to Eq. (4)-(7).

$$Z_1 = \left(R_1 + j\omega_0 L_1 + \frac{1}{j\omega_0 c_1} \right) \quad (4)$$

$$Z_2 = \left(R_2 + j\omega_0 L_2 + \frac{1}{j\omega_0 c_2} \right) \quad (5)$$

$$Z_m = (j\omega_0 M) \quad (6)$$

$$Z_L = (R_L) \quad (7)$$

To estimate the main and secondary currents, resolve Eq. (3) to be:

$$I_1 = \frac{V_s(Z_2 + Z_L)}{Z_1(Z_2 + Z_L) - Z_m^2} \quad (8)$$

$$I_2 = \frac{V_s Z_m}{Z_1(Z_2 + Z_L) - Z_m^2} \quad (9)$$

The induced voltage from primary to the secondary coils can be found by:

$$V_{12} = Z_m I_1 \quad (10)$$

The value of reflected impedance (Z_r) is determined by three variables: load impedance, capacitance, and receiver impedance, which are calculated by dividing the transmitter-dependent voltage by the transmitter current, as given in Eq. (11):

$$Z_r = V_{12}/I_1 = Z_m^2/(Z_2+Z_L) \quad (11)$$

While the relationship between the primary and reflected impedances to find input impedance (Z_{in}) as shown:

$$Z_{in} = Z_1 Z_m^2 / (Z_2 + Z_L) \quad (12)$$

Finally, Eq. (13) and Eq. (14) are utilized to determine the transmitted power (P_t) and output power (P_L), as illustrated [8].

$$P_L = \text{Re}(Z_L^*) |I_2|^2 / 2 \quad (13)$$

$$P_t = \text{Re}(Z_m^*) |I_1|^2 / 2 \quad (14)$$

3. System Methodology Design

This section deals with coil design and methodology of sliding mode controller and consists into two subsections: coil parameters and sliding mode controller.

3.1. Coil Parameters

This research focused on the efficacy of a dynamic WPT system for EV charging that included a controller and a converter. The wireless power transfer system still works and is made up of 19 transmitter coils and one receiving coil. The coil in this study was created using previous studies, and its specifications are: 20 turns, 70 mm inner radius, 3 mm wire radius, 2 mm air gap between turns, and 170 mm outer radius. Each coil has circular in form and the same size [8].

3.2. Sliding Mode Controller

Sliding mode control is particularly useful for systems with high nonlinearity and unpredictable dynamics. It might also be used in systems that need external disturbance rejection. This technology is widely used in the aerospace, automotive, and robotics fields. It is used for speed control in electric motor systems. It has several properties, including quick dynamic reactivity and sensitivity to changes in plant variables and outside influences. The controller's operating idea is to compel the system to stay on the sliding surface where the required characteristics will emerge by using an appropriate control approach. The design of a sliding mode controller includes sliding coefficient selection, sliding surface function design, control input selection, and noise reduction [37]-[40]. Fig. 3 shows block diagram for sliding mode controller.

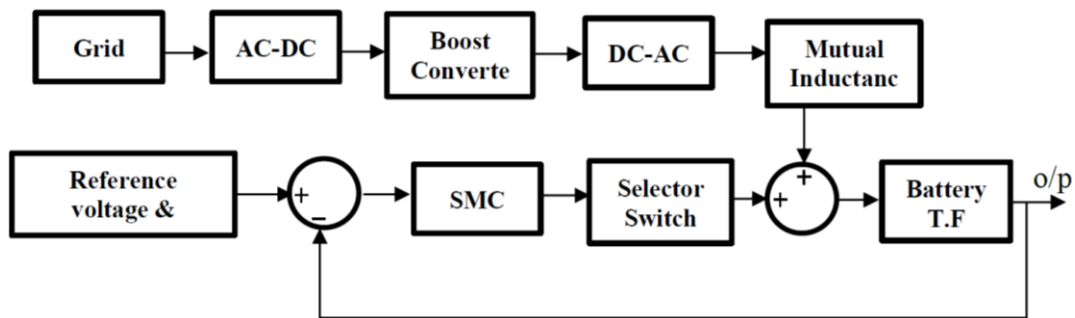


Fig. 3. Sliding mode control diagram

Consider a dynamic system based on the differential equation shown [37].

$$\dot{x}(t) = f(x, t) + g(x, t)u(x, t) + d(t) \quad (15)$$

Where, $f(x,t)$ refers to the system's intrinsic dynamics, $g(x,t)$ refers to an input function that modifies the impact of the control input $u(x,t)$ on the system, and $d(t)$ refers to an external disturbance that influences the system's behavior continually.

4. Results and Discussions

The EVs were constructed with both transmitter and receiver side. The primary part generates high voltages and consists of a three-phase voltage source (380 volts at 50 Hz), an AC-DC converter, and boost converter type diode. Electricity is transformed to DC-AC high frequency utilizing inverter-type insulated-gate bipolar transistors (IGBT). The receiving section consists of a mutual inductance (six coils), an AC-DC rectifier and a lithium-ion battery. Demonstrate in Fig. 4. The simulation design has been implemented using MATLAB 2022b. Also, Table 1, demonstrates the properties of the simulation model for an EV wireless charging system based on electrical circuit components.

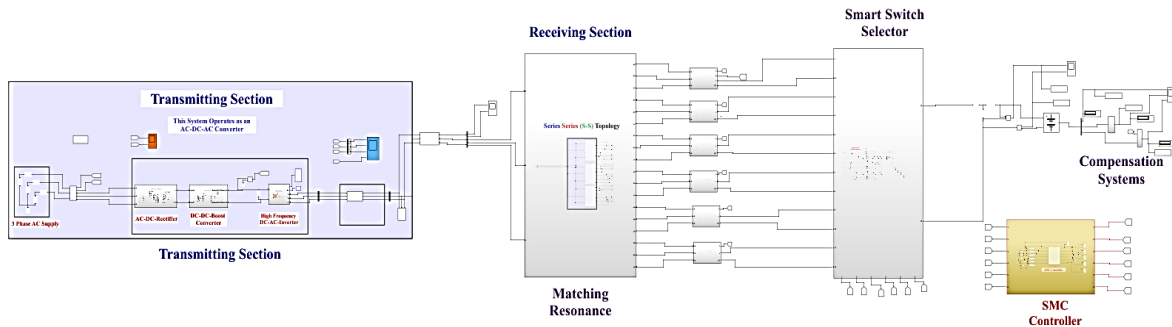


Fig. 4. MATLAB simulation model for wireless charging of EV with sliding mode controller

Table 1. The characteristics of EV system

Parameters	Value
Input voltage	380 V
L for ac-dc converters	200mH
C for ac-dc converters	5000 μ F
Switching frequency	20KHz
L for dc-cd boost converter	250 μ H
C for dc-cd boost converter	0.0005F
Switching frequency for dc-ac converter	20KHz
L filter	2mH
Mutual inductance	
R _m	0.005 Ω
L _m	85.4 μ H
Battery Parameters	
Type of Battery	Lithium-Ion
Nominal voltage	800 v
Initial state-of-charge (%)	10 %

These studies used CC-CV strategy with SMC to keep the current and voltage constant throughout the charging process. This design enhanced both the system's efficiency and battery life. The approach was enhanced by connecting many coils in series to the main receiving coil, which is activated dependent on the battery's charging needs. Fig. 5 demonstrates the relationship between voltage (V) and time (sec), with SMC monitoring the charging process to keep 800 volts. Within 500 seconds of charging, Stage 1: CC In this initial stage, the charging system supplies a constant current to the battery at the battery's safe maximum. The voltage rises rapidly and steadily over time. This rise reflects the battery's increasing State of Charge (SoC). The goal of this stage is to charge the battery to its maximum capacity as quickly as possible. The constant voltage stage then begins. When the battery voltage reaches its predetermined maximum of approximately 800 volts, the charging system moves to Stage 2. In this stage, SMC stabilizes the voltage at this level. While the voltage is constant, the current drawn by the battery gradually decreases. This stage continues until the current drops to zero reached 1500 second, meaning the battery is almost fully charged. This stage is necessary to safely complete the battery charge without causing stress or damage. This technique maintains a compromise between charging speed and battery safety, making it perfect for electric vehicles (EVs).

Fig. 6 illustrates the charging current in A on the vertical axis and time in seconds on the horizontal axis. This curve demonstrates the performance of a wireless DC fast charging technique for charging an electric car battery using a SMC. At the beginning of the charging process, the current is observed to rapidly increase to a maximum value of 100 A. This is the beginning of the constant current (CC) charging phase. The rapid increase indicates the controller's rapid response to reach the target charging current. The time period (approximately 50 to 1500 seconds). The battery voltage reaches its maximum (approximately 800 V), and SMC stabilizes this voltage. As a result, the charging current begins to reduce. As the battery gets closer to full charge, the current keeps dropping. The charging process typically ends when the current drops to zero, indicating that the battery is fully charged.

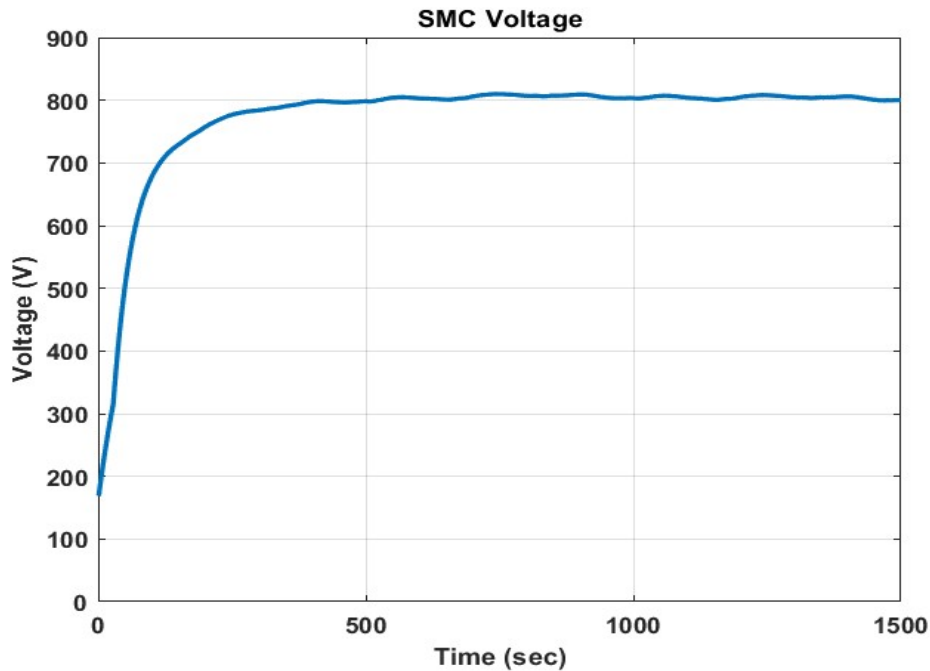


Fig. 5. Battery voltage

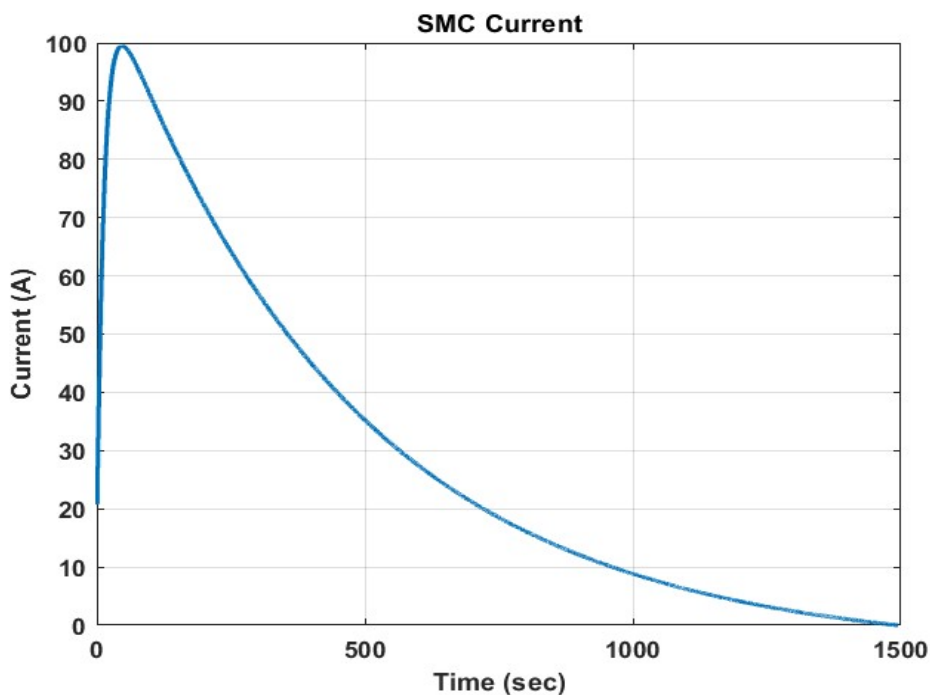


Fig. 6. Battery current

Fig. 7 depicts the battery charge status using a SMC. The curve begins at 10% and reaches 100% within 25 minutes. The curve is a regular linear shape, indicating that the charge increases at a consistent rate throughout the charging period. This implies that the system continually delivers energy into the battery, with no interruptions or fluctuations.

This research was compared with a previous study [18] that used neuro-fuzzy and fuzzy logic controllers with only CC technology, where the battery voltage reached 325V. In this study, CC-CV technology was employed with SMC and multiple coils on the receiving side, and the battery voltage reached 800V. As a result of increasing the number of coils, more power was transferred; on the other hand, the controller was able to regulate the current and voltage to preserve battery life.

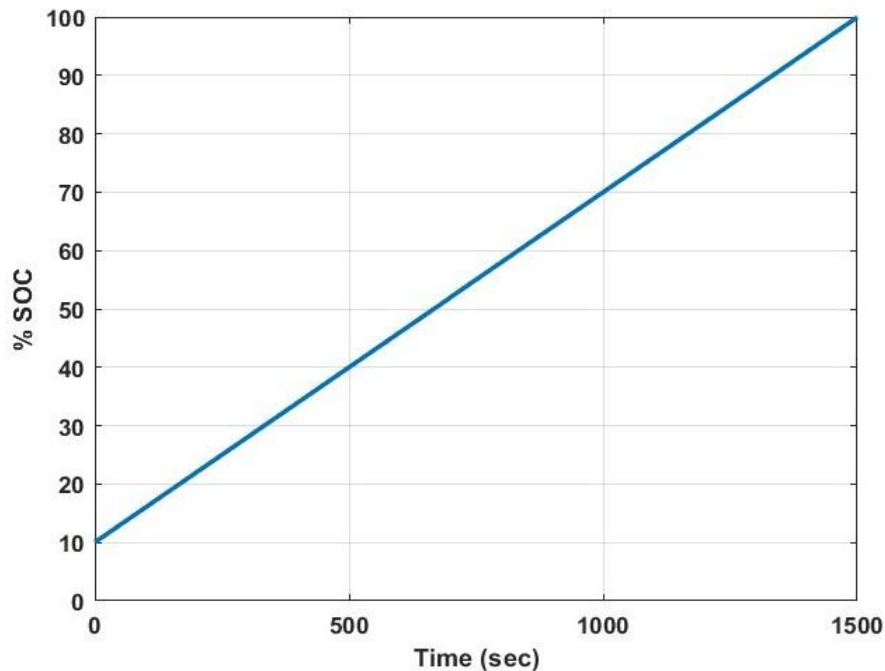


Fig. 7. State of charge for lithium battery

5. Conclusions

The current work proposed a resonant inductive wireless charging system using SMC. Level 3 DC fast charging was chosen by designing six coils in receiving coil with the use of booster on the transmitting side. SMC succeeded in keeping the voltage value extremely near 800 V during the charging period as it worked very efficiently to maintain a balance between charging speed and battery protection. Also, the performance of a SMC was characterized by its ability to gradually reaching the target of current 100 amps and reducing the current reached to zero meaning the battery is almost fully charged, in addition to ensure the efficiency and safety of charging without fluctuations or excesses. Finally, the system's ability to charge the battery up to 100% in a very short time of 1500 seconds was a great advantage for wireless charging systems. On the other hand, it was noted that there were no sharp fluctuations or oscillations the efficiency of the system and the stability of the charging process. Future study will include experimental verification of real vehicles and explore future expansions of this control method.

Author Contribution: The corresponding author tasks included writing the research, designing the system, and extracting results. As for authors Hesham Salim Anead and Khaled Faisal Sultan, their tasks included defining the research idea, verifying the results, and reviewing the research.

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