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Efficient Super-Twisting Sliding Mode Control for Dynamic Wireless Power Transfer to Electric Vehicles

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Abstract—

In light of the meteoric rise in popularity of EVs in recent years, this article illustrates how the need for dependable and rapid charging infrastructure has skyrocketed. A seemingly ready-made solution, Dynamic Wireless Power Transfer (DWPT) enables electric vehicle (EV) charging while in motion, doing away with the need for fixed charging infrastructure. In this research, we provide a way to improve the performance of a wireless charging system that is dynamic and uses the Super-Twisting Sliding Mode Control approach. By improving charging efficiency and maintaining voltage stability, the suggested STSMC controller ensures excellent, dependable, and stable power transmission while taking system uncertainties and disturbances into account. The method of control guarantees a downward power fluctuation, which improves dynamic responsiveness while keeping energy supply constant to the moving EV. The design and execution of DWPT system are simulated with several key disturbances, including misalignment, load variation, and changes in the coupling coefficient, taken into consideration. While compared to classical controllers, STSMC has the benefits of being resilient against shocks, reducing steady-state errors, and improving power transfer efficiency. The results show that the proposed control technique is effective, therefore it may be used for real-time electric vehicle charging. Our program promotes environmentally friendly transportation by making the most of wireless charging capabilities in future electric vehicle networks.

Keywords— MATLAB /Simulink, Dynamic Charging Controller, STSM Controller, Magnetic Resonance Coupling (MRC), Inductive Wireless Power Transfer (IWPT), Wireless Power Transfer (WPT) and Electric Vehicles (EVs).

INTRODUCTION

Increasing world temperatures are a result, in part, of the myriad of dangerous pollutants produced by automobiles powered by internal combustion engines (ICEs). One way to break the cycle of carbon emissions and reliance on fossil fuels is to power electric vehicles (EVs) using renewable energy. Despite their claimed energy density, lithium-ion batteries are cumbersome, costly, and take forever to charge. The expanded scope. Although there are fast-charging stations, the whole process still takes less than half an hour and is both expensive and inconvenient. Quickly replace your dead batteries with fully charged ones at battery changing stations. Electric vehicles require robust and well defined networks of interconnected charging facilities. The most common on-board and off-board plug-in charging systems use cumbersome power cords that are easy targets for theft, damage, and annoyances caused by faulty connections. Nikola Tesla's method of wireless power transfer (WPT) ensures the safety of such receivers by replacing cables with electromagnetic waves, allowing for power transmission without touching. Modular, automated EV charging stations could be a real possibility with this innovation. Effective WPT requires advanced control strategies.

To guarantee excellent power efficiency and provide the flexibility to modify tracking accuracy, Model Predictive Control (MPC) has emerged as a significant technology for power electronic converters used in electric vehicle (EV) wireless charging. High computing costs, shutdown sensitivity to model quality, and instability against rapid interruptions are drawbacks with MPC. It gets around these problems by making the system more micro-robust and removing the chattering effect. Through refinements of energy flow that eliminate chattering effects, this further ensures a continuous and effective flow of energy for the WPT-based EV charging. There will be a significant shift toward more environmentally friendly transportation options, and one of those options is the transition from ICEs to EVs, or electric cars.

LITERATURE REVIEW

Using adaptive dynamic programming (ADP) to optimize the power supply and charging power, J. Liu et al. [1] investigated a system for dynamic wireless electric vehicle (EV) charging that uses adaptive control. Factors such as user satisfaction, road load strain, power supply cost, and stability were considered in the research. Through the use of neural network forecasting and reduction of the long-term cost function, an approximation optimum control approach was accomplished. The results of the simulation showed that there was a good equilibrium between charging load, customer contentment, cost-effectiveness, and supply stability. Future research will broaden the model to include a wider range of electric vehicle types and charging protocols. Adaptive vehicle position control for electric vehicle (EV) Dynamic Wireless Charging (DWC) based on long short-term memory (LSTM) is described in [2].dealt with problems caused by improperly oriented transmitter and receiver coils that reduced the efficiency of power transmission. The electric vehicle was able to adjust its trajectory by using a multi-layer LSTM architecture to identify the optimal lateral position with the strongest electromagnetic field. The simulation findings demonstrated a 162.3% improvement in EV charging efficiency compared to the conventional lane-based methods. To find out what happens to society and the economy, researchers will look into large-scale simulations and actual applications in the future. One method for optimizing the efficiency of dynamic wireless charging (DWC) systems was suggested in [3,11], which combines a constant current (CC) charging control system with an algorithm. The method they developed allowed for more efficient energy transfer and reliable CC charging with just a secondary active rectifier and no wireless connection between the two sides. On a 1.5 kW experimental setup, the optimization procedure led to an improvement of 3% in efficiency, reaching a maximum of 85%. The control of constant voltage (CV) charging will be the focus of future research in an effort to further improve performance. To improve the performance of robotic manipulators in the presence of uncertainties, a high-quality, robust super-twisting sliding mode control (HOST-SMC) method has been suggested and is associated with. In order to improve the performance of robot manipulators in the face of uncertainties and disturbances, robust composite higher-order super-twisting sliding mode control (HOST-SMC) is suggested in [4,14].

Their technique offers significant improvements in robustness, trajectory tracking accuracy, and chattering reduction compared to standard Sliding Mode Control (SMC). Reducing the impact of unknown dynamics and external disturbances while maintaining improved stability and control precision is achieved via the simulation. Going forward, we will strive for both practical implementation and more optimization. The authors of [5,12] suggested a controller for real-time quad rotor trajectory tracking called FSTSMC, which combines a higher-order sliding mode observer with finite-time super-twisting. They minimized chattering and guaranteed limited time convergence of the tracking errors by focusing on the unmeasured states and external disturbances. Using the DJI Matrice 100 quad rotor for online testing and simulation, the newly suggested method outperformed conventional SMC approaches in terms of tracking accuracy while requiring much less control effort. Improving disturbance estimates and expanding the controller's applicability to more complicated UAV settings will be the focus of future study. Improved performance of surface-mounted permanent magnet synchronous motors (SPMSMs) was documented in a new high-order sliding mode control paradigm based on the novel super twisting algorithm (NSTA) in [6,13]. By including an adaptive term into the proportional section of the algorithm, the classical examples of the super twisting approach were able to improve upon their low reaching rate and poor disturbance rejection. Less chattering, improved anti-disturbance, and faster reaction time were the outcomes of the simulation. Improving performance even further is the goal of the next effort, which will center on maximizing the sliding mode benefit. The impact of magnetic coupling on nonadjacent resonators in wireless power domino-resonator systems was the subject of an original inquiry. An important aspect of enhancing wireless power transfer (WPT) systems is reducing interference from nonadjacent resonators, which may boost energy transfer efficiency. The work in [7] emphasized the complexities of this task. Circles and non-coaxial axes were considered in [8, 9]. In a similar vein, we looked closely at electric vehicle charging systems, highlighting how state-of-the-art materials and control technology enhance power delivery and the user experience. The essay highlights the collaborative efforts of control engineering and material science in powering WPT devices. provided solid groundwork for further investigation on resonator arrangement. Through delving into bidirectional WPT systems, we offer new designs for energy feedback and grid interaction that tackle sustainability and energy efficiency issues. We also identify structural factors that impact power transfer efficiency and provide basic design guidelines for practical applications. Contributed to the body of knowledge by investigating WPT (two-way wireless power transfer) systems in [10,15]. To aid in the improvement of energy efficiency and sustainability, they brought innovative designs that enable energy to be sent back and interact with the power system. Domino resonator systems were studied, and structural elements influencing energy transfer efficiency were found. Additionally, realistic design guidelines were proposed.

PROPOSED METHODOLOGY

The simulation model incorporates a power transfer system, a super-twisting sliding mode controller, and a groundbreaking improved approach to the high-frequency inverter to provide the best possible power supply during Dynamic Wireless Charging of electric cars. Primary coils implanted in the road manage the flow of power and wirelessly distribute it to secondary coils installed on cars. Primary transmission coils embedded in the road convert DC power to high-frequency AC, secondary receiver coils in the vehicle capture and convert the transmitted energy to DC, and an AC/DC power supply unit with grid or renewable power sources is used to generate an electromagnetic field. An STSMC-based control circuit reliably controls the flow of power to the HF inverter by means of a PWM generator, while a rectifier and power management system regulate the current, voltage, and compliance during battery charging. According to Faraday's Law of Induction, a changing magnetic flux induces an electromotive force (EMF) in a coil, which is essential for power transmission:

$$E = -\frac{d\Phi}{dt} \qquad (1)$$

In order to transmit electricity wirelessly, the secondary coil induces a voltage that is:

$$V_s = j\omega M I_p \qquad (2)$$

The induced voltage is denoted by s (2) V, the frequency is measured in angular units, M stands for the mutual inductance, and I p is the main current that flows through the coil. The following elements affect the efficiency of power transmission η for different resonant circuits: coil alignment, coupling coefficient, and quality factors.

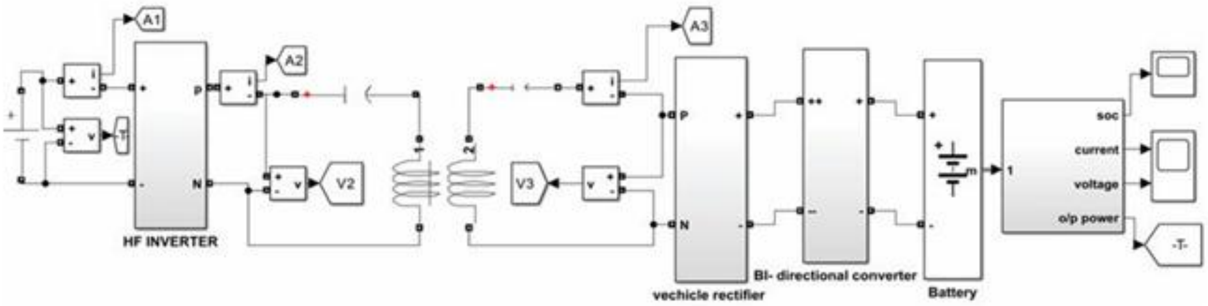


Fig. 1. Schematic diagram of dynamic wireless charging of electric vehicle

$$\eta = \frac{P_{out}}{P_{in}} \quad (3)$$

power in (supplied to the transmitter) and power out (supplied to the vehicle) are represented by and, respectively. The coupling coefficient, k, may be calculated using the following formula.

$$k = \frac{M}{\sqrt{L_1 L_2}} \quad (4)$$

The mutual inductance, and the inductances of the main and secondary coils are represented by M and and, respectively. The amount of power that is received at the secondary coil is:

$$P_S = \frac{\omega^2 M^2 I_P^2}{R_S} \quad (5)$$

Among the many components that make up the control system are the following: a pulse width modulation (PWM) generator for efficient switching pulses, a control system that dynamically adjusts power based on vehicle speed and battery state of charge (SOC), and compensation networks that optimize power transfer and impedance matching in order to maintain resonance efficiency.

$$\omega^2 LC = 1 \quad (6)$$

Subsystems such as an HF inverter (which produces AC voltage), a car module (which inductively powers a receiver coil), and a rectifier (which uses a bi-directional converter to convert AC to DC for charging batteries) are all coupled in the Simulink diagram. To maintain system stability in the presence of misalignment, the STSMC-based control system regulates inverter switching. Critical performance indices are assessed by simulation for the model, which includes monitoring of current and voltage waveforms, system efficiency, and the consequences of coil misalignment. The simulation also keeps an eye on power transfer efficiency, which is measured by quality factors and coupling coefficients, in addition to

CONTROL STRATEGIES

For constitutive control nonlinear systems that take external disturbances into consideration and adopt a being-model framework, a Super-Twisting-Mode Control System provides a form of strong supervision that ensures the system will converge to and stay on a predefined sliding surface, rendering it immune to both external and internal uncertainties. Reading more on STSMC requires looking at its mathematical description, principles of operation, stability analysis, and many applications.

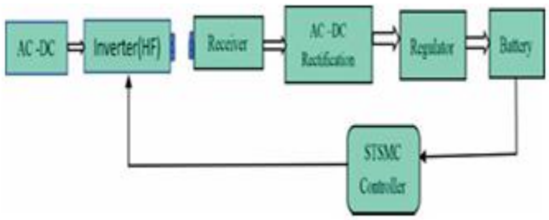


Fig. 2. Block Diagram of STSMC-Based Wireless Power Transfer System

A state-space representation of this system may be obtained in the following way.

$$x = Ax + Bu + d \quad (7)$$

The system's state variables (x) include things like location, velocity, etc., and the control input (u) is what makes the system work. d stands for the system's uncertainties and outside influences. Matrix A and matrix B determine the system dynamics. To accomplish the desired behavior of the system, we provide the following definition of the sliding surface S(x):

$$S(x) = Cx \quad (8)$$

where C is a carefully selected design matrix that guarantees the system's states will converge. Consequently, STSMC seeks to effectively push and maintain the system state on this sliding surface for control optimality and robustness against uncertainty.When you get to that point, nothing can bother you. The chattering that occurs when using a discontinuous law, which is not desired in real-world applications, is a common problem with traditional Sliding Mode Control (SMC). By incorporating second-order sliding mode control based on a Super-Twisting Algorithm (STA), ST-SMC improves upon this to provide a more smooth and chatter-free convergence into the sliding surface.Here is the ST-SMC law:

$$u = -k_1 \mid S(x)^{1/2} sign(S(x)) - k_2 S(x) \qquad (9)$$

Two tuning parameters, 1 k and 2 k, influence the controller's performance and take on positive values. Quick convergence to the sliding surface is guaranteed by 1/2 S x sign S x, although chattering is reduced. The extra 2 ( ) kS x term will dampen the system reaction even more, stabilizing it. We use Lyapunov's stability theorem to the system analysis in order to determine stability. This candidate for the Lyapunov function is:

$$V(S) = \frac{1}{2} S^2 \qquad (10$$

Taking its time derivative:

$$V = SS = S(-k_1 \mid S \mid^{1/2} sign(S) - k_2 S) \qquad (11$$

In order to achieve stability, the system states must converge towards equilibrium and exhibit behavior free of divergence. Control operations that smooth out and avoid many excessive switchings are guaranteed by the Super-Twisting Algorithm. Think about the higher-order Lyapunov function : to go further into the stability analysis.

$$V(S) = \frac{1}{2} S^2 + \int_0^t \mid S \mid^{3/2} dt$$

Differentiating,

$$V = SS + \mid S \mid^{3/2}$$

Substituting S from the STSMC law,

$$V = S(-k_1 \mid S \mid^{1/2} sign(S) - k_2 S) + \mid S \mid^{3/2}$$

$$V = -k1 \mid S \mid^{3/2} - k_2 S^2 + \mid S \mid^{3/2}$$

$$V = (-k_1 + 1) \mid S \mid^{3/2} - k_2 S^2$$

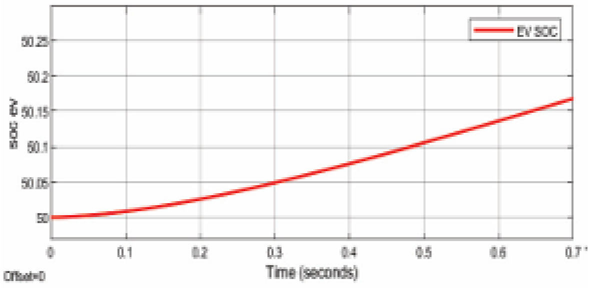
As 0 V is guaranteed because 1 1 k and 2 0 k , we may conclude that there is global stability. Based on the system's dynamics, the optimal values for k1 and k2 will provide a balance between robustness and responsiveness. Typically, it is founded on:

$$k_1 > 1, k_2 > 0, \lambda_3, \lambda_4 > 0 \qquad (17)$$

Optimal performance may be achieved by the use of experimental tuning approaches, such as adaptive gain scheduling or Lyapunov-based tuning. In contrast to standard SMC, which exhibits the chattering problem, super twisted sliding mode control (STSMC) is resistant against uncertainty. Thus, STSMC enhances control precision and assurance by easing a control rule that forces a system onto a specified sliding surface. The mathematical description of the strategy ensures its theoretical stability, while the given simulation block diagram serves as an example for practical application of the control approach. As a result, this article provides a thorough framework for studying, designing, and implementing STSMC's many technical applications. V.

SIMULATION RESULTS AND DISCUSSIONS

A dynamic wireless charger for electric vehicles (EVs) was developed in this article using the MATLAB Simulink platform. The proposed Wireless Power Transfer (WPT) dynamic charging system consists of a magnetic coupler and carefully engineered power electronics converters. The STSMC controller also serves to provide system control pulses. We evaluate this system's efficacy using a number of performance metrics.



voltage and current on the battery side, which characterize the reliability and effectiveness of the receiving process. The voltage is kept within a certain range of operation to ensure that the battery gets power effectively. The voltage is constant and there are no fluctuations that might damage the battery. These waveforms' smoothness proves that the control strategy worked.

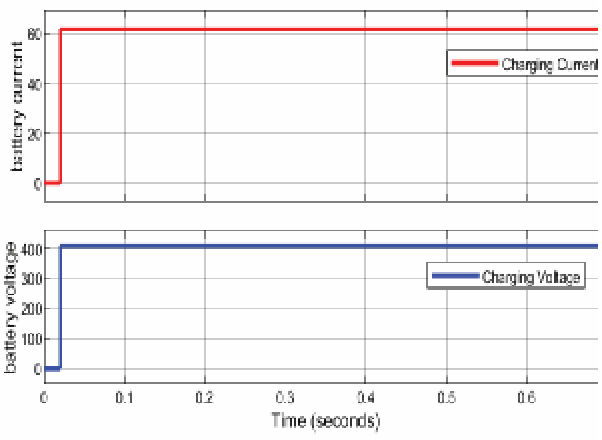


Fig. 4. EV Current and EV Battery Voltage

The voltage supplied to the wireless charger's transmitting coil is seen in this graph. This voltage is being generated and controlled by power electronics, and its steady waveform indicates that they are all functioning properly. The efficiency of the secondary side's power transfer will be disrupted if this voltage is problematic.

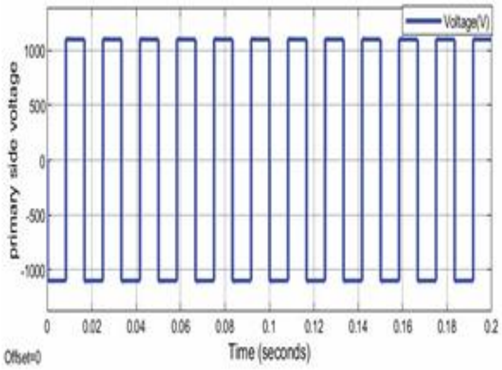


Fig. 5. Primary side voltage

An electric vehicle's secondary side voltage is the voltage that the receiving coil receives. In order to guarantee power transmission to the car battery, this voltage waveform has to be steady and high enough. The investigation confirmed the coupling and control strategy's efficacy as the secondary voltage did not change.

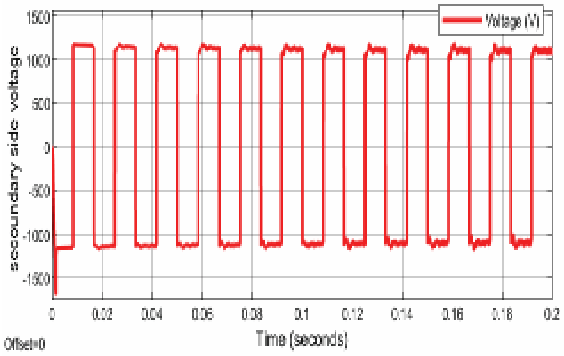


Fig. 6. Secondary Side Voltage

You can see the current flowing through the transmitting coil in the main side current waveform. Accurate wireless power transmission is guaranteed by a well managed electromagnetic field produced by currents. In order to avoid overheating and excessive losses, the results show that the system can control the current.

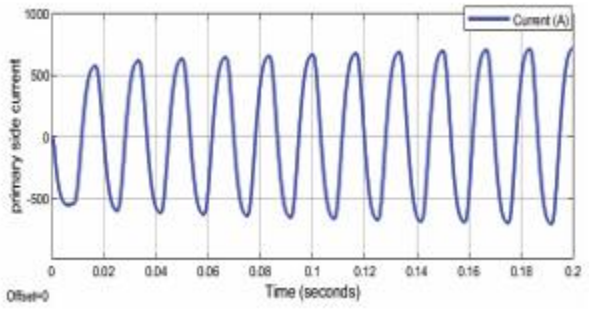


Fig. 7. Primary side current Secondary side current is defined as the one that is received by the onboard charging system of the EV.

A flat wave indicates efficient energy transfer with low transmission losses, which suggests the system can convert that energy into electricity for the electric vehicle's battery.

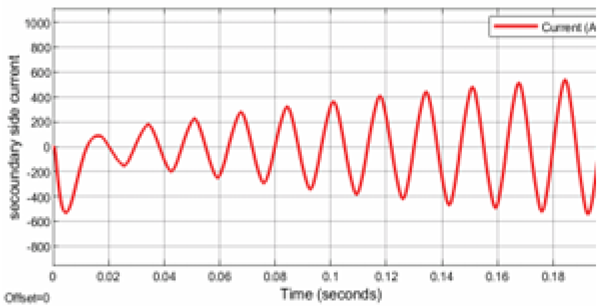


Fig. 8. Secondary side current

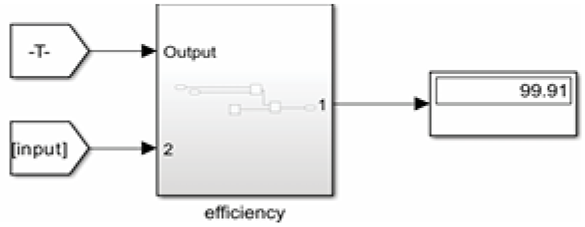


Fig. 9. Overall Efficiency

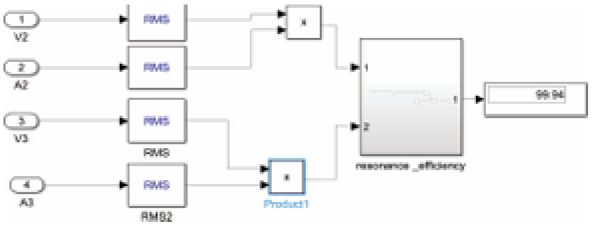


Fig. 10. Resonance Efficiency

TABLE I. COMPARISON OF MPC AND STSMC

PARAMETER	Using MPC	Using STSMC
Power Efficiency (%)	98.82	99.81
Resonance Efficiency (%)	99.37	99.94
Primary Side Voltage (V)	1100	1100
Secondary Side Voltage(V)	1100	1100
Primary Side Current(A)	800	800
Secondary Side Current(A)	795.2	799.8

CONCLUSION

799.8 total An evaluation of STSMC in an EV Dynamic Wireless Charging System shows that it performs better than MPC. Both controllers provide stability of main and secondary voltages at 1100 V and primary current at 800 A. However, STSMC has a greater secondary current (799.8 A) than MPC (795.2 A), suggesting that STSMC provides better current regulation. STSMC ensures higher energy transfer by increasing power efficiency to 99.81% from 98.82% for MPC and resonance efficiency to 99.94% from 99.37% for MPC. The results show that STSMC is the better control technique for EV Dynamic Wireless Charging Systems in terms of power efficiency, loss reduction, and reliability.

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