



DYNAMIC WIRELESS POWER TRANSFER FOR IMPROVED ELECTRIC VEHICLE AUTOMATION

Resonant Power Stage Design, Controller Comparison and MATLAB/Simulink Validation

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Abstract : Electric vehicles (EVs) and vehicle automation are converging, yet plug-in and stationary wireless charging force a vehicle to stop and recharge, which limits the continuous operation of autonomous fleets. This paper investigates Dynamic Wireless Power Transfer (DWPT), in which road-embedded transmitter coils energise a vehicle-mounted pickup coil while the vehicle is moving. A system configuration comprising a rectifier-fed high-frequency inverter, resonant compensation networks, loosely coupled coils, a receiver-side rectifier and a battery interface is presented, together with a design procedure for the coil inductance, compensation capacitance and operating frequency. The coupled-circuit, resonance, power-transfer and state-space models are derived, and three controllers, namely PID/PI, model predictive control (MPC) and Active Disturbance Rejection Control (ADRC), with Linear Quadratic Integral (LQI) control as a state-space alternative, are formulated. A MATLAB/Simulink model of a 17 V to 34 V, 5–10 W, 30–50 kHz converter is simulated; its output settles at about 36.5 V within roughly 5 ms. The comparative transient study shows that ADRC gives the smallest overshoot, the shortest settling time and the best disturbance rejection under coupling and load variations, followed by MPC and then PID. Loss and current-ripple mechanisms and their mitigation are also discussed. The results indicate that DWPT with robust control can support continuous, uninterrupted operation of automated EVs while allowing smaller onboard batteries.

IndexTerms - Dynamic wireless power transfer, electric vehicle automation, inductive power transfer, LCC compensation, maximum power point tracking, active disturbance rejection control, MATLAB/Simulink.

I. INTRODUCTION

The global shift towards sustainable transportation has accelerated the adoption of electric vehicles (EVs), which offer lower greenhouse-gas emissions, higher energy efficiency and lower running cost than internal-combustion vehicles. In parallel, advances in sensing, communication and artificial intelligence are driving the development of autonomous and semi-autonomous driving. A major obstacle to the large-scale deployment of electric and automated vehicles is, however, the availability of efficient, reliable and convenient charging infrastructure [1], [2].

Conventional plug-in charging and stationary wireless charging both require the vehicle to stop for an extended period. For an automated fleet, such as autonomous public transport, logistics or ride-sharing, this idle time reduces utilisation and forces the use of heavy and costly battery packs to limit the number of charging stops. Dynamic Wireless Power Transfer (DWPT) removes this limitation by transferring energy to the vehicle while it is in motion. Transmitter coils are installed beneath the road surface and a receiver coil is mounted under the vehicle; as the vehicle passes over the charging lane, energy crosses the air gap through the magnetic field and is delivered to the battery or directly to the traction drive [2], [3]. Because the energy is supplied continuously, the onboard battery can be smaller and lighter, which lowers vehicle weight and cost and improves overall energy efficiency.

In the context of automation, DWPT offers a second benefit. The sensors, cameras, computing units and communication modules of an automated vehicle need a stable and uninterrupted supply, and any interruption of the energy supply directly affects performance and safety. Continuous en-route charging keeps the state of charge within a narrow band, and the roadside infrastructure can be linked to the vehicle through vehicle-to-infrastructure (V2I) communication so that power transfer is coordinated with vehicle position, speed and energy demand. The autonomous steering function can also be used to keep the vehicle in the lane position that gives the best coil alignment, thereby merging power management with navigation.

Practical DWPT nevertheless remains challenging. The coupling coefficient between the road and vehicle coils varies continuously with lateral misalignment, air gap and speed; resonance is easily detuned; the high-frequency power electronics generate switching and magnetic losses; electromagnetic interference and human exposure must be limited; and the infrastructure cost is high [3], [4]. A well-designed resonant power stage and a controller that is robust to these continuously changing conditions are therefore central to a viable system.

The objectives of this work are to:

- analyse how DWPT improves the operational efficiency of automated EVs by reducing dependence on stationary charging, extending range and permitting smaller, lighter batteries;
- develop the system configuration, design equations and component-sizing procedure of the resonant power stage;
- investigate the integration of DWPT with autonomous driving and V2I communication;
- compare PID, model predictive control (MPC) and Active Disturbance Rejection Control (ADRC) in MATLAB/Simulink under coupling and load disturbances; and
- assess system losses, current ripple, electromagnetic safety and economic challenges, and identify directions for future work.

The paper is organised as follows. Section II reviews the literature on wireless power transfer, converter topologies, maximum power point tracking (MPPT) and control. Section III presents the system configuration and design. Section IV develops the mathematical model, and Section V formulates the control strategies. Section VI reports and discusses the simulation results, and Section VII concludes the paper and outlines future scope.

II. LITERATURE REVIEW

A. Foundations of Wireless Power Transfer for EVs

Kurs et al. demonstrated mid-range wireless energy transfer through strongly coupled magnetic resonances [5], which laid the foundation for later work on transport applications. Covic and Boys reviewed inductive power transfer (IPT) systems and discussed their operating principles, technological development, coil alignment, magnetic-field optimisation and the feasibility of large-scale deployment in public transport [1]. Wang et al. set out design considerations for a contactless EV battery charger, including the choice of resonant compensation and its influence on power transfer [6]. Li and Mi surveyed wireless charging for EV applications and identified efficiency, misalignment tolerance and cost as the principal issues [2], and Mi et al. reviewed advances in wireless power transfer for roadway-powered EVs [3].

B. Coil and Compensation Topologies

The most widely used topology in DWPT is IPT, based on magnetic coupling between a primary coil embedded in the roadway and a secondary coil in the vehicle. The series-series (SS), series-parallel (SP), parallel-series (PS) and parallel-parallel (PP) compensation networks are the usual candidates [7]. SS compensation is often preferred for EV applications because of its simplicity and relatively stable current output, but its performance is affected by changes in coil alignment and air gap, which are unavoidable in dynamic operation. To overcome this limitation, resonant topologies with LCC and LCL compensation have been introduced. They provide higher efficiency, lower reactive-power loss and better tolerance to misalignment, which makes them attractive for moving vehicles [8]. Coil geometry also matters: circular, rectangular and double-D (DD) pads are common, and DD pads give better misalignment tolerance and flux distribution [9].

Segmented or track-based DWPT divides the road into several coil segments that are energised only when a vehicle is above them. This reduces energy wastage and electromagnetic exposure, but requires precise vehicle detection and sequential switching of the segments [4]. Capacitive power transfer (CPT) uses electric fields between plates; it offers lower electromagnetic interference and simpler structures but a lower power capability, which makes it less suitable for high-power EVs. Hybrid inductive-capacitive structures have been proposed to combine the advantages of both, and bidirectional topologies that support vehicle-to-grid (V2G) operation are attracting increasing attention.

C. DC-DC Power-Conversion Stage

A DC-DC stage regulates the rectified output on the vehicle side or the DC link on the roadside. Table I compares the common converter classes. Non-isolated converters are simple and inexpensive but provide no isolation; isolated converters, such as the flyback and the dual active bridge (DAB), provide safety isolation and, in the case of the DAB, bidirectional power flow; resonant converters (LLC and CLLC) achieve the highest efficiency through soft switching but are sensitive to load variation [10].

TABLE I. COMPARISON OF DC-DC POWER CONVERTER TOPOLOGIES

Class	Type	Typical efficiency	Power level	Key advantage	Major limitation
Non-isolated	Buck / Boost	83–93 %	Low–Medium	Simple, low cost	No safety isolation
	Interleaved buck	Up to 99 %	Medium–High	Low current ripple	Complex control
Isolated	Flyback	80–90 %	Low (<500 W)	Very simple, isolated	High switch stress
	DAB	92–96 %	High	Bidirectional flow	High circulating current
Resonant	LLC / CLLC	95–98 %	High	Soft switching (ZVS/ZCS)	Sensitive to load

D. Evolution of MPPT Algorithms

MPPT algorithms ensure that the maximum possible power is transferred from the roadside transmitter to the vehicle receiver while vehicle speed, coil alignment, air gap and load continuously change. Early systems used the Perturb and Observe (P&O) method because of its simplicity [11]. P&O perturbs a control variable, observes the change in power and keeps or reverses the direction accordingly; it oscillates around the maximum power point in steady state and responds poorly to rapid changes. Incremental Conductance (INC) improves tracking accuracy by comparing incremental and instantaneous conductance, but still struggles when coupling and alignment vary rapidly. Fuzzy-logic MPPT handles uncertainty and nonlinearity through linguistic rules and gives faster response and smaller oscillation, while artificial neural network (ANN) and machine-learning methods learn the system behaviour from data and predict the optimal operating point. Hybrid methods, such as P&O combined with fuzzy logic or an ANN, and optimisation-based methods, such as particle swarm optimisation (PSO) and genetic algorithms (GA), improve speed and avoid local maxima at the cost of computational complexity. In DWPT these algorithms are increasingly integrated with V2I communication so that the power level follows vehicle position and demand.

E. Control Methodologies

PID control is the most common method for regulating output voltage or current in DWPT converters because it is simple and inexpensive, but its fixed gains adapt poorly to nonlinear and time-varying behaviour. Model predictive control (MPC) uses a model to predict future behaviour and optimise the control action over a horizon, which handles constraints and multivariable interaction and gives better damping and faster settling [12]. Resonance-frequency control, for example with phase-locked loops, keeps both coils tuned to the same frequency under misalignment and varying air gap. Adaptive, fuzzy and ANN-based controllers improve robustness and response time, and coordinated control with V2I communication adjusts the power level to traffic, location and energy demand. Active disturbance rejection control (ADRC) [13] estimates the lumped internal and external disturbance with an extended state observer and cancels it in real time, which is attractive for DWPT because the coupling, misalignment and load act as time-varying disturbances.

F. Research Gap

Most published studies are simulation based, and few compare PID, MPC and ADRC under identical dynamic coupling and load conditions. The coordination of the power-transfer controller with automation functions, such as lane keeping for optimal coil alignment and V2I-based segment activation, also remains largely open. This paper addresses these points through a unified design, modelling and comparative simulation study.

III. SYSTEM CONFIGURATION AND DESIGN

A. Proposed System Configuration

The proposed DWPT system consists of three subsystems: the ground-based transmitting unit, the vehicle-mounted receiving unit and the control and communication module. The transmitting unit is embedded beneath the road and comprises segmented primary coils, a high-frequency inverter and a power-supply converter. The coils are laid along the lane so that energy transfer is continuous as the vehicle moves, and each segment is activated only when a vehicle is detected in its vicinity, which improves efficiency and reduces unnecessary loss. The vehicle-mounted unit comprises a secondary coil, a rectifier, a DC–DC converter and a battery management system. The receiving coil captures the magnetic field of the transmitter, and the induced energy is rectified and regulated before it is supplied to the battery or the electric drivetrain.

The control and communication framework is the key feature that links the infrastructure to the vehicle. Detection sensors installed along the roadway identify the presence and position of the EV and inform the control unit, which energises the corresponding transmitter segments. V2I communication allows real-time exchange of data between the vehicle and the infrastructure so that the power level is adapted to speed, load demand and alignment. Fig. 1 shows the block diagram of the implemented system. The AC mains supplies a rectifier with a MOSFET stage that drives the transmitter coil. The receiver coil feeds a rectifier that charges the vehicle battery, which can also be supplemented by a photovoltaic (PV) panel. A voltage-measurement block monitors the battery and passes the signal to an Arduino controller, which drives an LED charging indicator and an IoT module for remote monitoring.

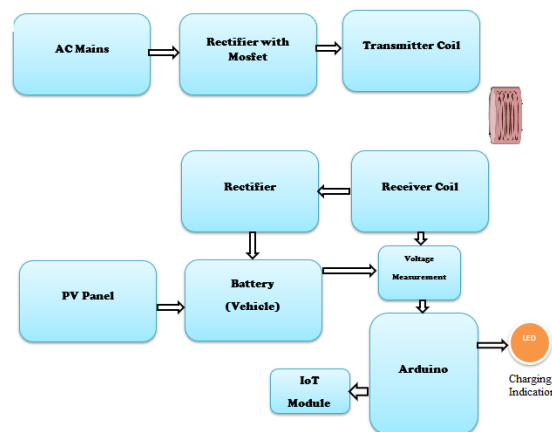


Fig. 1. Block diagram of the wireless charging system

B. Working of the Transmitting and Receiving Sides

On the transmitting side the 220 V, 50 Hz AC supply is stepped down to 12 V by a transformer and converted to pulsating DC by a full-bridge rectifier. A 12 V RMS supply corresponds to a peak of about 17 V, which is the 17 V DC input listed in Table II. A fixed-duty-cycle high-frequency inverter then drives the wireless power transfer (WPT) circuit at its resonant frequency. A constant voltage source and a resistive load are used for the basic implementation, and they are later replaced by the complete circuit of Fig. 2, which shows the double-sided LCC-compensated structure: a DC source feeding a full-bridge inverter (S_1 – S_4), the primary LCC network (L_p , C_a , C_p), the inductively coupled coils (L_p , L_s), the secondary LCC network (C_s , L_b , C_b), a diode bridge rectifier (D_1 – D_4), a filter capacitor C_0 and the battery.

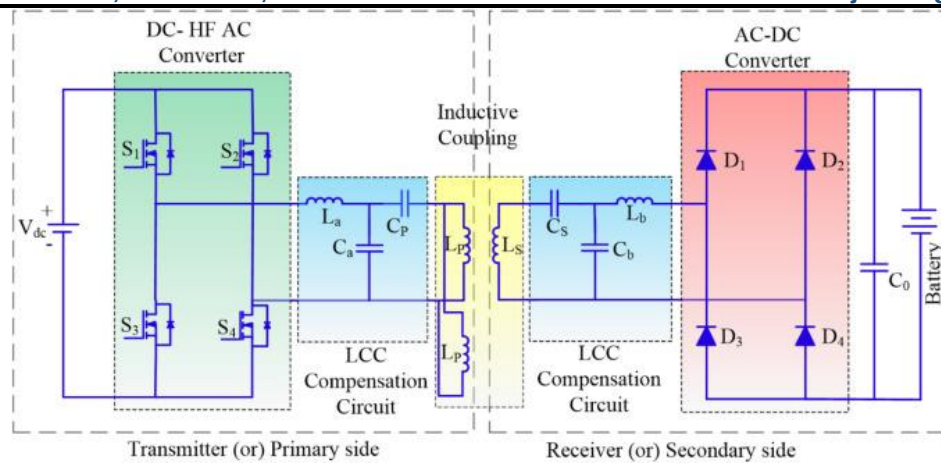


Fig. 2. Circuit diagram of the LCC-compensated wireless power transfer system

On the receiving side the secondary coil, placed at the bottom of the vehicle, receives the energy from the primary coil on the charging pad. The induced alternating current is converted to direct current by the rectifier. A capacitor filters the rectified voltage, reduces interference and maintains a consistent voltage level, and a potentiometer acts as a variable resistor for fine tuning of the voltage for specific subsystems. The resulting DC charges the vehicle battery, which then powers the vehicle.

C. Design Specifications

The specifications adopted for the simulated converter are given in Table II. The values correspond to a low-power laboratory-scale model that reproduces the behaviour of a full-scale system, whose typical parameter ranges are listed in Table III in Section VI.

TABLE II. DESIGN SPECIFICATIONS OF THE WIRELESS POWER TRANSFER (WPT) SYSTEM

S. No.	Parameter	Value
1	Input voltage (transmitter)	17 V
2	Output voltage (receiver)	34 V
3	Rated output power	5 to 10 W
4	Switching frequency	30–50 kHz
5	Inductors (L_1, L_2)	220 μ H
6	Resonant capacitance (calculated from (1))	≈ 46 nF (50 kHz) to 128 nF (30 kHz)

D. Inductor and Coil Selection

The inductance of the primary and secondary coils must be chosen so that resonance is achieved at the intended operating frequency, normally in the 20–100 kHz range, which balances efficiency, component size and electromagnetic compatibility. For medium-power EV applications the power per segment is typically 3–20 kW, and the coupling coefficient k between the coils in dynamic conditions lies between 0.1 and 0.5. The coil geometry determines the misalignment tolerance. DD coils are preferred in EV applications; rectangular coils are easier to install in the roadway; circular coils give uniform flux but are less tolerant to lateral displacement. The number of turns sets the inductance and field strength, but a larger number of turns also raises the resistance and copper loss, so a trade-off is required. Litz wire is used to limit skin-effect and proximity-effect losses at high frequency.

Ferrite cores are widely used for their high permeability and low core loss, and ferrite shielding directs the flux towards the receiver and reduces interference with surrounding structures; air-core coils avoid saturation but need larger dimensions. The quality factor Q and the inductance tolerance determine the resonant efficiency, so high- Q coils with mechanical robustness suitable for road installation are selected. Copper and eddy-current losses heat the coil, and thermal management with heat sinks, ventilation and temperature-resistant insulation keeps the temperature rise within the limit needed for long-term reliability.

E. Capacitor Selection

Capacitors in the compensation network form the resonant circuit with the coil inductance. The resonant frequency is

$$f_0 = 1 / (2\pi\sqrt{LC}) \quad (1)$$

so for a given inductance and frequency the required capacitance is $C = 1/[(2\pi f_0)^2 L]$. For the 220 μ H inductors of Table II this gives about 46 nF at 50 kHz and 128 nF at 30 kHz. In series compensation the capacitor is connected in series with the coil to cancel its inductive reactance; in parallel compensation it is connected in parallel to improve voltage stability; LCC compensation is preferred in modern DWPT because it provides constant-current or constant-voltage characteristics and better misalignment tolerance. Any deviation from the optimal capacitance detunes the system, reduces efficiency and increases loss, so precise sizing is essential.

Polypropylene film capacitors are normally used because of their low equivalent series resistance (ESR), high stability and excellent thermal performance; electrolytic capacitors are avoided at high frequency because of their higher loss and lower reliability. The voltage and current ratings must withstand the high AC voltages in the resonant circuit, including the variation caused by misalignment and load changes, with a safety margin. Low ESR and a low temperature coefficient also contribute to a high quality factor of the resonant circuit.

F. Modes of Operation and Equivalent Circuits

Because of vehicle motion the DWPT system operates in three modes that differ in the degree of magnetic coupling. In the *no-load or idle* mode no vehicle is above the coil; the transmitter is deactivated or operates at minimum power, and the equivalent circuit consists only of the primary coil, its compensation capacitor and the inverter. In the *partially coupled* mode the vehicle has entered the charging zone but the alignment is not optimal; the coupling coefficient and mutual inductance are low, the efficiency

is moderate, and control action is required to compensate for the misalignment. In the *fully coupled* mode the vehicle is optimally aligned, the mutual inductance is high, resonance is achieved through the compensation capacitors and the system operates near its maximum power-transfer capability.

In all modes the equivalent circuit consists of the primary inverter, the resonant compensation networks, the coupled inductors representing the transmitter and receiver coils, and the rectifier and load on the secondary side. It may be represented as a series or parallel resonant circuit depending on the compensation (SS, SP or LCC), and the mutual inductance M links the primary and secondary circuits. In segmented tracks, selective connection and disconnection of the primary segments as the vehicle moves introduces additional switching modes into the equivalent circuit.

IV. MATHEMATICAL MODELLING

The DWPT system is modelled as a loosely coupled transformer consisting of a primary coil (transmitter) and a secondary coil (receiver). The self-inductances are L_1 and L_2 , the resistances are R_1 and R_2 , and the coupling is represented by the mutual inductance M . The voltage equations of the coupled circuit are

$$V_1 = R_1 I_1 + j\omega L_1 I_1 + j\omega M I_2 \quad (2)$$

$$V_2 = R_2 I_2 + j\omega L_2 I_2 + j\omega M I_1 \quad (3)$$

where V_1 , V_2 and I_1 , I_2 are the coil voltages and currents and ω is the angular frequency. The mutual inductance and the quality factor are

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

$$Q = \omega L / R \quad (5)$$

where k ($0 \leq k \leq 1$) is the coupling coefficient, which depends on the alignment and air gap and is not constant in dynamic operation because it changes continuously as the vehicle moves over the transmitter segments. A higher Q means lower energy loss. At resonance, given by (1), the reactive components cancel and the power delivered to the load R_L of an SS-compensated system is

$$P_{out} = \omega^2 M^2 V_1^2 R_L / [R_1(R_2 + R_L) + \omega^2 M^2]^2 \quad (6)$$

which shows that the power depends strongly on the mutual inductance, the operating frequency and the load. The efficiency is

$$\eta = (P_{out} / P_{in}) \times 100 \% \quad (7)$$

and it is reduced by coil misalignment, air-gap variation, resistive loss and switching loss in the power electronics. Since these quantities vary continuously during motion, real-time modelling and control are required. In segmented systems the model also contains switching functions that represent the activation and deactivation of coil segments according to the vehicle position; these make the parameters time varying and the model nonlinear. For controller design the system is therefore expressed in state-space form

$$\dot{x} = Ax + Bu, \quad y = Cx + Du \quad (8)$$

where x contains the coil currents and capacitor voltages, u is the input voltage (or inverter duty cycle) and y is the output voltage, current or power. The matrices **A**, **B**, **C** and **D** describe the system dynamics and the coupling behaviour.

V. CONTROL STRATEGIES

A. Perturb and Observe Tracking

In a DWPT system the coupling, resonant frequency and efficiency fluctuate as the vehicle moves, so the controller must keep the system at its best operating point by adjusting the switching frequency, the inverter duty cycle or the impedance-matching network. The P&O algorithm does this by continuously perturbing a control variable. Its steps are:

- 1) measure the voltage and current and calculate the power $P_{new} = V \times I$;
- 2) apply a small perturbation to the control variable (duty cycle or switching frequency);
- 3) measure the new power and compare it with the previous value P_{old} ;
- 4) if $P_{new} > P_{old}$ keep the direction of perturbation, otherwise reverse it, then set $P_{old} = P_{new}$ and repeat.

P&O is simple, has a low computational cost and needs no model, but it oscillates around the maximum point, may follow the wrong direction under rapid changes and responds slowly in highly dynamic systems. Adaptive step size, combination with fuzzy logic or an ANN, and combination with the INC method are the usual improvements.

B. PID and PI Control

The PI/PID controller regulates the output voltage or current from the error between the reference and measured values, $u(t) = K_p e(t) + K_i \int e(t) dt + K_d de(t)/dt$. With fixed gains it responds quickly in stable conditions, but it produces overshoot and oscillation when the coupling changes suddenly, and it does not adapt to the nonlinear, time-varying plant.

C. Model Predictive Control

MPC uses the model (8) to predict the output over a horizon N and selects the input sequence that minimises the cost function

$$J = \sum_{j=1}^N [(y_{ref} - \hat{y}_{k+j})^2 Q + (\Delta u_{k+j-1})^2 R] \quad (9)$$

subject to input and state constraints, and applies only the first element of the sequence at each step. The predictive action reduces overshoot and gives smoother convergence, but accuracy depends on the model and the computational effort is higher.

D. Active Disturbance Rejection Control

ADRC consists of a tracking differentiator (TD), an extended state observer (ESO) and a nonlinear state error feedback (NLSEF) law. The TD smooths the reference and generates its derivative, the ESO estimates the states and the total disturbance, and the NLSEF generates the control signal from the estimated states. In the DWPT system the relative motion of the coils, the coupling variation, the parameter uncertainty and the load change are lumped into a single *total disturbance* f that is estimated and cancelled in real time. The linear version (LADRC) simplifies the design and is easy to implement in Simulink, DSPs and microcontrollers.

For a plant approximated as $\dot{y} = f + b_0 u$, a third-order linear ESO with states z_1, z_2, z_3 and gains $\beta_1 = 3\omega_o, \beta_2 = 3\omega_o^2, \beta_3 = \omega_o^3$ [14] gives

$$\dot{z}_1 = z_2 + \beta_1(y - z_1), \quad \dot{z}_2 = z_3 + b_0 u + \beta_2(y - z_1), \quad \dot{z}_3 = \beta_3(y - z_1) \quad (10)$$

$$u = (u_0 - z_3) / b_0, \quad u_0 = k_p(r - z_1) - k_d z_2, \quad k_p = \omega_c^2, \quad k_d = 2\omega_c \quad (11)$$

where ω_o and ω_c are the observer and controller bandwidths. ADRC does not need an accurate mathematical model, which suits the DWPT plant whose mutual inductance and coupling coefficient change dynamically and are difficult to model precisely.

E. Linear Quadratic Integral Control

LQI extends the linear quadratic regulator with integral action to remove the steady-state error. The model (8) is augmented with the integral state x_i , where $dx_i/dt = r - y$, the control law is $u = -\mathbf{K}_x \mathbf{x} - K_i x_i$, and the gains are obtained by minimising [15]

$$J = \int_0^\infty (\mathbf{x}_a^T \mathbf{Q} \mathbf{x}_a + u^T \mathbf{R} u) dt, \quad \mathbf{x}_a = [\mathbf{x}; x_i] \quad (12)$$

The weighting matrices $\mathbf{Q}$ and $\mathbf{R}$ balance the response speed, stability and control effort. LQI gives zero steady-state error under varying load, handles the interaction between voltage, current, frequency and coupling within one state-space framework, and shows better damping than a conventional PID controller.

VI. SIMULATION RESULTS AND DISCUSSION

A. Simulation Setup

The DWPT system is simulated in MATLAB/Simulink using an equivalent-circuit model of loosely coupled inductive coils. The model includes a DC source, a high-frequency full-bridge inverter, the resonant compensation, the coupled inductors, a rectifier and a load representing the EV battery (Fig. 3). Vehicle movement is represented by varying the coupling coefficient k with time, and the segmented-coil logic energises only the segments beneath the vehicle. The recorded quantities are the output power, efficiency, voltage regulation, current waveform and transient response. The parameter ranges that represent a full-scale system are given in Table III; the laboratory-scale operating point is that of Table II.

TABLE III. TYPICAL SIMULINK PARAMETER RANGES FOR A FULL-SCALE DWPT SYSTEM

Parameter	Range	Parameter	Range
DC input voltage	400–800 V	Load resistance (battery)	5–50 Ω
Switching frequency	20–100 kHz	Sampling time	1–100 μ s
Coil inductance (L_1, L_2)	50–300 μ H	Vehicle speed	0–25 m/s
Coil resistance (R_1, R_2)	0.1–1 Ω	Power per segment	3–20 kW
Coupling coefficient k	0.1–0.6	Component temperature	< 80 $^\circ$ C

In the model, PWM signals drive the full-bridge inverter on the transmitter side, and the AC power is supplied to the primary through a high-frequency transformer and series inductance. The receiver side contains the secondary inductance, the rectifier bridge, the output capacitor C_o and the resistive load, with voltage and current measurement blocks and scopes at the main points. The mutual coupling is represented by coupled-inductor blocks in which k is varied during the run. A feedback loop regulates the output against the reference, and PID, MPC or ADRC controllers adjust the inverter switching signals. In advanced configurations MPPT is added, and thermal and stress analysis can be included to verify that the components remain within safe limits.

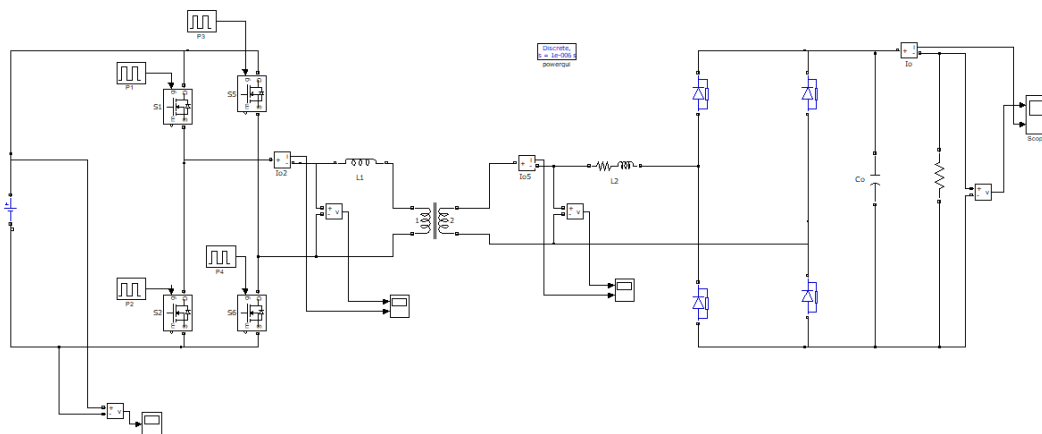


Fig. 3. MATLAB/Simulink model of the simulated converter

B. Steady-State Waveforms

Fig. 4 shows the waveforms recorded at the main points of the model. The input to the inverter is a constant 17 V DC (Fig. 4a), which corresponds to the rectified 12 V RMS supply. The inverter converts it into a square-wave voltage of ± 17 V (Fig. 4b); the lower trace shows the inverter output current, a triangular waveform with a peak of about ± 5.5 A, as expected for a series inductance supporting a square-wave voltage. The transformer secondary voltage (Fig. 4c) is a square wave of about ± 38 V, consistent with the 1:2 step-up from 17 V to 34 V, with short transients at each switching edge and a very small current. After rectification and filtering, the output voltage rises smoothly to about 36.5 V and the output current to about 0.087 A, that is, about 3.2 W, and both settle in roughly 5 ms without overshoot (Fig. 4d).

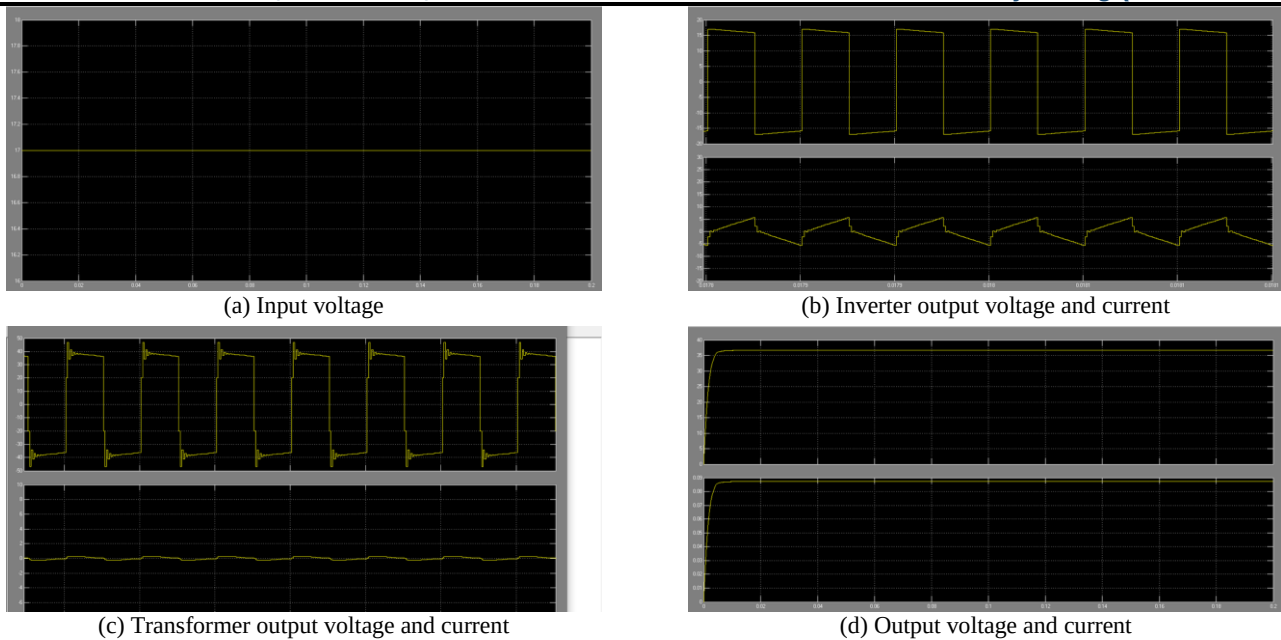


Fig. 4. Simulated waveforms: (a) input voltage, (b) inverter output voltage and current, (c) transformer output voltage and current, (d) output voltage and current of the converter

The output voltage is about 2.5 V (7 %) higher than the 34 V design value, which shows that closed-loop regulation, as formulated in Section V, is needed to hold the output at the set-point. The simulation confirms that maximum power transfer occurs when the coupling coefficient is at its optimal value, corresponding to correct alignment of the coils. Under ideal alignment the resonance between the inductive and capacitive elements gives high efficiency, whereas increasing misalignment gradually reduces the output power, which demonstrates the sensitivity of DWPT to position. LCC and SS compensation networks sustain the voltage better under varying load than basic topologies by reducing reactive-power loss.

C. Dynamic Response and Segment Transitions

Transient behaviour is evaluated by introducing step changes in the load resistance, the coupling coefficient and the input voltage. They represent an EV entering or leaving a charging zone, experiencing misalignment or changing speed. When the vehicle enters the zone the coupling rises rapidly, for example from 0.1 to 0.5, which causes a transient surge in output power; the controller then adjusts the inverter switching and resonance conditions until the output stabilises. When the vehicle leaves the zone the power decreases smoothly, which avoids abrupt disturbances. When the segmented coils are activated in sequence, a smooth power transition is observed and the energy delivery remains continuous. Under optimal control the stabilisation time is a few milliseconds, and proper resonance tuning minimises the energy loss during transients.

D. Comparative Controller Performance

The controllers are judged by rise time, settling time, overshoot and steady-state error. The PID controller performs acceptably in stable conditions but shows higher overshoot and oscillation, a longer settling time and noticeable power fluctuation when the coupling changes suddenly, because its fixed gains cannot follow the changing dynamics. MPC predicts future behaviour and optimises the input, which gives smaller overshoot, faster settling and smoother transitions, although its performance depends on model accuracy and it needs more computation. ADRC provides the best transient performance: the ESO estimates the total disturbance and compensates it in real time, which gives minimal overshoot, very fast settling and nearly smooth power transfer with minimal deviation during transitions between transmitter segments. ADRC also keeps the most stable output voltage with negligible steady-state error and is the most robust to coil misalignment, inductance variation and load change; the same trends appear in the current response and in the efficiency stability. The comparison is summarised in Table IV.

TABLE IV. QUALITATIVE COMPARISON OF CONTROLLER TRANSIENT PERFORMANCE

Criterion	PID	MPC	ADRC
Rise time	Moderate	Fast	Fast
Overshoot	High	Reduced	Minimal
Settling time	Longest	Short	Very short
Disturbance rejection	Limited (fixed gains)	Good (prediction)	Excellent (ESO)
Voltage regulation	Larger fluctuation	Slight deviation	Negligible steady-state error
Power during segment change	Noticeable fluctuation	Reduced oscillation	Nearly smooth
Model dependence	Low	High	Low (model-free)
Computational effort	Low	High	Moderate

The state-space LQI controller of Section V lies between PID and ADRC in this ranking: its integral action removes the steady-state error and its full-state feedback improves damping compared with PID, but, unlike ADRC, it does not actively estimate and cancel the unmodelled disturbance.

E. System Loss and Current Ripple

System loss consists of copper, core, switching and transmission losses. Copper loss in the coils is proportional to the square of the winding current and rises under heavy load and poor alignment. Core loss in the ferrite arises from hysteresis and eddy currents and increases at the 20–100 kHz operating frequency. Switching loss occurs in the MOSFETs or IGBTs during turn-on and turn-off, and transmission loss is the consequence of imperfect coupling, which depends on the vehicle position and the air gap. Current

ripple, caused by high-frequency switching and coupling variation, increases heating, shortens component life, causes electromagnetic interference and degrades the battery charging quality.

Several measures reduce these effects. Resonant SS or LCC compensation minimises reactive power, and operation at resonance keeps the voltage and current in phase. Litz wire reduces skin and proximity losses. Segmented coil activation energises only the coils beneath the vehicle, which lowers loss and interference. LC filters at the output stage smooth the current and give a stable DC output for the battery, while PWM optimisation, MPC and ADRC suppress ripple on the control side; ADRC estimates and compensates the disturbance in real time, which improves stability. Under resonant operation with proper compensation the current waveform is smoother and the efficiency is significantly higher, and with the advanced controllers the ripple amplitude is reduced further, which improves voltage regulation and charging performance.

F. Practical Challenges

The simulations also indicate the practical challenges that remain. The sensitivity of efficiency to misalignment calls for accurate position sensing, adaptive control and, for automated vehicles, lane keeping at the optimal lateral offset. Road-embedded coils require high installation and maintenance investment, electromagnetic exposure must be limited by shielding and compliance with standards, and the lack of common standards for frequency, coil design and communication limits interoperability between manufacturers.

VII. CONCLUSION AND FUTURE SCOPE

This paper has examined Dynamic Wireless Power Transfer as an enabler of continuous, uninterrupted operation of automated electric vehicles. A system configuration with road-embedded segmented transmitters, a vehicle-side receiver and a control and V2I communication framework was presented, with design equations for the coil inductance and the compensation capacitance, a mathematical model based on coupled circuits and state space, and the formulation of PID, MPC, ADRC and LQI controllers. The MATLAB/Simulink study of a 17 V to 34 V converter showed an output of about 36.5 V that settles in roughly 5 ms, and the comparative analysis showed that ADRC gives the best transient performance, with minimal overshoot, the shortest settling time and the best disturbance rejection, followed by MPC and then PID. Resonant compensation, segmented activation and ripple filtering reduce the losses and current ripple. Continuous energy supply allows smaller and lighter batteries and thereby improves vehicle payload and efficiency.

Several directions remain for future work. Higher efficiency under strongly varying speed, alignment and air gap may be achieved with advanced coil designs, optimised compensation topologies and improved magnetic materials. Artificial-intelligence, machine-learning and deep-learning predictive control can learn driving patterns and optimise power transfer in real time. Cost-effective, modular and standardised road structures are needed to reduce the installation cost, and integration with solar and wind sources and bidirectional V2G/G2V energy flow would provide sustainable charging infrastructure. Better shielding and compliance with exposure limits, optimal battery sizing and hybrid energy storage, and global standards for frequency, coil design and communication are also required. Finally, since most existing studies, including the present one, are simulation based, full-scale test tracks and prototype vehicles are needed to validate the models and the controllers under real driving conditions.

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