

NINE-SWITCH QUASI-IMPEDANCE SOURCE INVERTER FOR DUAL-MOTOR ELECTRIC VEHICLE DRIVES WITH INTEGRATED ONBOARD CHARGING

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ARTICLE INFO

Article History

Received on: February 02, 2026

Reviewed on: March 03, 2026

Accepted on: April 01, 2026

Published on: July 31, 2026

Keywords:

Electric Vehicles,
Onboard Charger,
Nine Switch Inverter,
Quasi Z-Source Inverter.

ABSTRACT

With the significant advancements in the electric vehicle (EV) sector, improving electric conversion and charging systems has become necessary to improve efficiency and accessibility for all users. This paper introduces a novel nine-switch inverter with a quasi-impedance Source topology designed to revolutionize EV power train systems. The proposed inverter design enables the simultaneous control of two traction motors while reducing the number of required power switches from 12 to 9, saving three switches compared to the conventional dual-inverter setup, improving system redundancy and dependability for improved EV performance. Utilizing its features, the inverter doubles as an onboard charger, eliminating the need for a separate charging unit. This streamlined approach reduces system complexity and cost while improving charging convenience.



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I. INTRODUCTION

Global energy consumption keeps rising, and a constant desire exists to enhance power capacity. Most of this energy is derived from fossil resources, which presents ongoing energy production, conversion, and distribution challenges. It also contributes to pollution and its detrimental impact on the environment, particularly in urban areas, and human health. Transportation represents one of the most significant consumers, especially vehicles with internal combustion engines; however, advancements in the electric vehicle (EV) sector are leading to a gradual shift towards more sustainable transportation options, which links to the rapid penetration of renewable and alternative energy sources and energy storage solutions. These vehicles offer greater energy efficiency, minimal pollution, and reduced maintenance compared to traditional internal combustion engines [1]. Electric vehicles can be categorized into two main types based on the number and arrangement of motors: distributed multi-motor driven power trains and centralized single-motor driven power trains. Distributed multi motor driven power trains can be further classified into three subcategories: Dual-motor, as described in [2], Triple-motor as discussed [3], and Four-motor power trains, as explored in [4]. On the other hand, centralized single-motor driven is the most common configuration in modern EVs [5].

Compared to the centralized single motor approach, distributed multi-motor power trains offer several advantages, including higher efficiency, reduced torque pulsation, and improved fault tolerance. However, these benefits come at a higher premium price. In dual motor configurations, using two independent motors requires separate control. The conventional approach involves two separate inverters, leading to increased cost and system size [6]. Ongoing research in power electronics aims to develop cost-effective and efficient conversion capabilities. Reducing the number of semiconductor switches is a critical factor in converter costs. The decrease in converter size through fewer switches can significantly reduce the price. Various novel topologies have been created, including the Nine Switch Inverter (NSI) [7], the B4 inverter [8], and the Five Leg Inverter [9]. The NSI, a dual-output inverter, has been proposed as a solution in various industrial applications, helping to reduce the number of semiconductor switches and associated energy losses, as well as streamlining drive circuitry. Previous research on nine-switch and quasi-impedance source inverter (qZSI) topologies has explored several directions, but each remains limited in scope with respect to the requirements of electric vehicle systems.

Discontinuous PWM strategies for qZS nine-switch inverters [10] and carrier-based PWM techniques [11] mainly focused on reducing switching losses and improving modulation performance, without addressing dual-motor propulsion or onboard charging. Similarly, dual hysteresis band current control has been applied to nine switch inverters for two induction motors [12], but this work only emphasized torque control and omitted EV-specific functions such as bidirectional charging and vehicle-to-grid (V2G) operation. Other studies have attempted integrated drive and charger solutions: a nine-switch-based charger for six-phase machines [13], and a multilevel nine-switch topology with improved harmonic quality [14]. However, these approaches are constrained either by reliance on six-phase machines or by increased device count and circuit complexity, and they do not consider independent dual-motor platforms. In contrast, the present work introduces a unified qZS nine-switch inverter solution that simultaneously supports dual-motor EV propulsion with dynamic torque distribution and onboard charging using a constant-current/constant-voltage strategy. By combining propulsion, charging, and V2G functionalities within a single, compact converter, while maintaining the inherent advantages of the qZSI such as continuous input current and voltage boost capability, the proposed system offers a novel and more comprehensive EV-oriented architecture than previously reported in the literature.

II. ON-BOARD CHARGER FOR ELECTRIC VEHICLES

The Nine-Switch Inverter (NSI) enables dual three-phase outputs using shared switches but requires a higher DC-link voltage [15], and employing a two-stage boost converter increases cost and complexity. To address this, the Z-Source Inverter (ZSI) was introduced with single-stage buck–boost capability, though it suffers from discontinuous input current and higher source stress [16]. The Quasi Z-Source Inverter (QZSI) improves upon this by rearranging the impedance network, ensuring continuous input current, reduced ripple, elimination of inrush current, and simplified integration. Despite higher capacitor voltage stress, it offers better efficiency and control. Its voltage boost is characterized by the boost factor.

$$B = \frac{1}{1 - 2D} \quad (1)$$

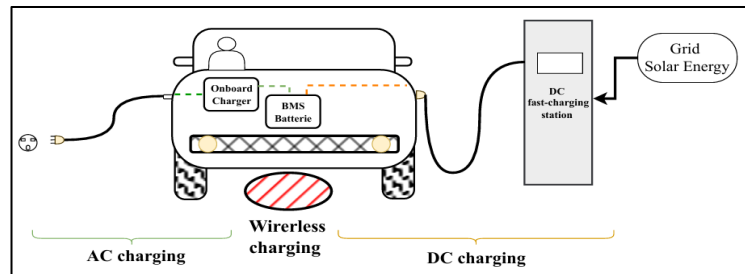


Figure 1: Schematic representation of differences in on-board, off-board chargers, and Wireless chargers or DC-fast charging station.
Source: Authors, (2026).

Where D is the shoot-through duty ratio, confirming its ability to provide single-stage buck–boost operation suitable for renewable and electric vehicle applications. Moreover, such inverter topologies not only enable efficient traction power conversion but also contribute to improved power quality by maintaining low Total Harmonic Distortion (THD) as represent (Figure 2).

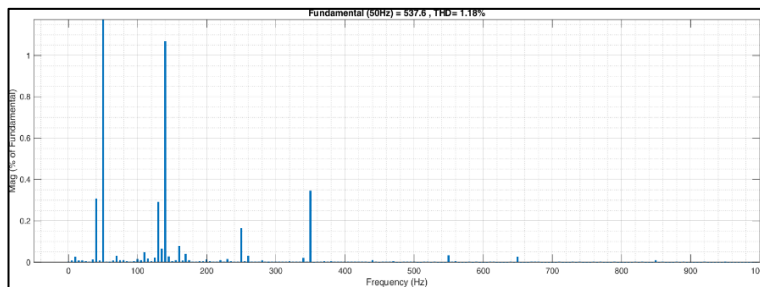


Figure 2: THD The Simple Boost Control.
Source: Authors, (2026).

Charging systems for hybrid and electric vehicles are crucial for efficient operation. They are categorized into off-board and on-board systems, as shown in (Figure 1), which power the batteries and enable efficient operation. Onboard charging systems are integrated into the vehicle itself. These systems include components like the onboard charger, charging port, charging control unit, power conversion, and protection mechanisms [17], which offers a significant advantage for EVs by enabling them to charge wherever an electrical outlet is available. This flexibility allows EV owners to conveniently charge their vehicles home by converting external AC power into DC. The onboard charging system regulates voltage and current, ensuring efficient and safe power transfer to the vehicle's batteries [18], [19]. On the other hand, the Off-board charging stations are external to the vehicle, typically part of the charging infrastructure [20], which offers High-DC power allows fast charging and ensures compatibility with different EV models and standards. However, it is important to consider the challenges associated with the off-board charging station. The availability of these stations is limited due to the need for dedicated parking spaces, which can be challenging in urban areas. The setting up off-board charging infrastructure is expensive, especially for high-power DC fast charging stations, and requires regular maintenance [21]. The choice between Off-board and Onboard charging depends on the user's specific needs, driving patterns, and access to charging infrastructure.

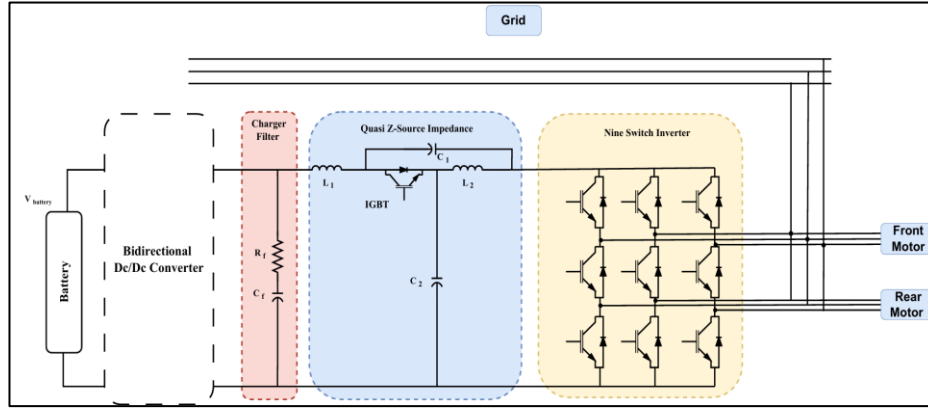


Figure 3: The proposed bidirectional Quasi Z-Source Nine Switch inverter.
Source: Authors, (2026).

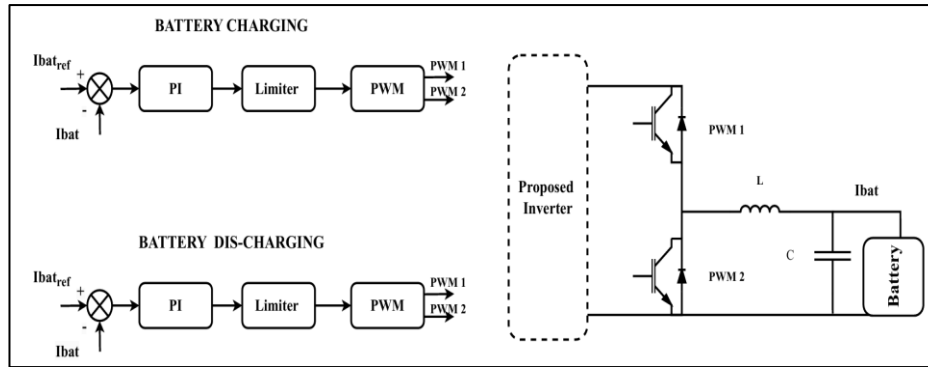


Figure 4: Battery Charger Controller.
Source: Authors, (2026).

(Figure 3) represents the proposed inverter in this topology. We can operate in two directions. The first one, the battery, powers the two motors through the inverter. The second operation uses a bidirectional DC-DC converter to achieve the desired input voltage and current for the battery, as in (Figure 4). The power flows from the grid to the battery utilizing the operation control (Figure 5) V2G, G2V, mentioned in [22].

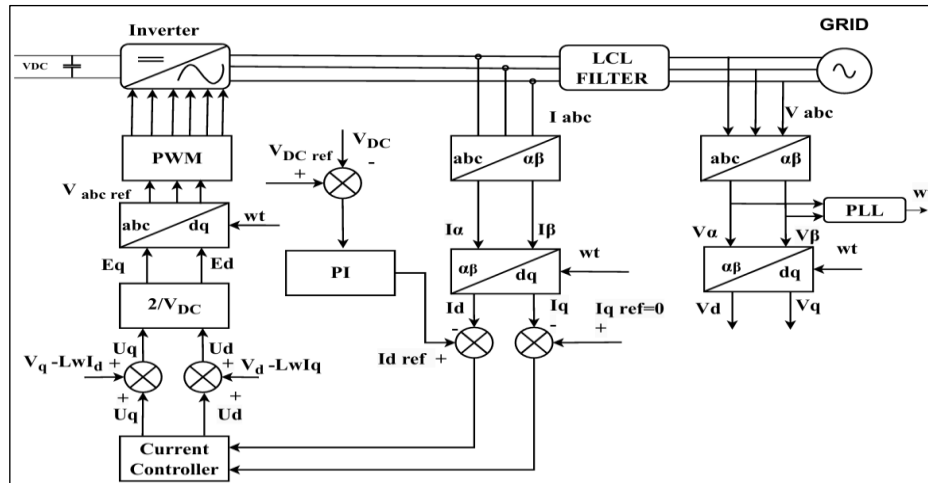


Figure 5: A diagram illustrating the flow of power from the grid to vehicles in a Grid-to-Vehicle (G2V) system.
Source: Authors, (2026).

III. CHARGING MODE FOR BATTERY IN ELECTRIC VEHICLE

The electrification of the transportation sector has led to research on battery electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) and how they can be integrated into electrical networks. Electric vehicles' charging method significantly impacts their batteries' performance and efficiency and determines the charging mode [23]. There are two primary charging modes for batteries in EVs: constant-current (CC) charging and constant-voltage (CV) charging [24]. The constant current (CC) charging mode is generally used during the initial stages when the battery has a low state of charge. SOC. By providing a controlled, constant current to the battery for fast charging, however, as the battery reaches higher charge levels, the charging rate gradually decreases [25].

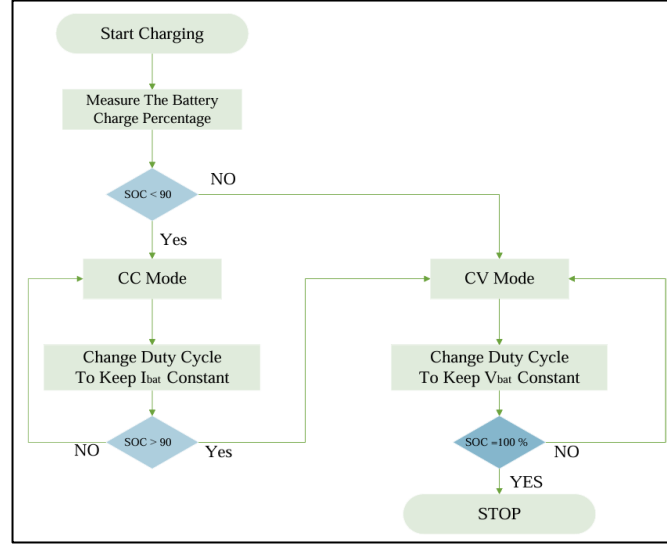


Figure 6: Charging Mode.

Source: Authors, (2026).

In contrast, constant voltage (CV) is used in the late stages of charging near full capacity by providing a constant voltage to the battery during charging. The CV method ensures that the charging current decreases as the battery's state of charge increases, preventing overcharging, which can be detrimental to its performance and lifespan [26]. The decision to use CC or CV charging mode depends on various factors, including battery chemistry, charging infrastructure, and desired charging time. The algorithm used to charge the battery is represented in (Figure 6). Two charging modes were used: constant current and followed by constant voltage.

IV. DYNAMIC VEHICLES

In order to understand the behavior of a vehicle, it is important to consider the various forces acting upon it. These forces are crucial in determining the vehicle's speed, acceleration, and fuel efficiency. There are four main forces that an electric vehicle must overcome in order to move: Grading Resistance, Rolling Resistance, Aerodynamic Drag, and Inertial Effect. Understanding these forces can help us optimize the design of electric vehicles and improve their performance on the road [27-30]. Grading resistance (F_g) is the force that opposes a vehicle's movement due to changes in elevation or slope. It is related to the vehicle's weight and the road's gradient. The higher the gradient, the greater the grading resistance.

$$F_g = M_{car} \cdot g \cdot \sin(\alpha) \quad (2)$$

Where: M_{car} [kg] Mass of the vehicle.

$g = 9.81$ [m/s²] Free fall acceleration.

α [rad] Angle of the driving surface.

Rolling resistance (F_r) is the force that resists a vehicle's movement due to the deformation of its tires as they come into contact with the road. Rolling resistance depends on various factors, such as tire type, tire pressure, and road surface.

$$F_r = M_{car} \cdot g \cdot C_r \cdot \cos(\alpha) \quad (3)$$

where: C_r [-] Tire rolling resistance coefficient.

Aerodynamic drag (F_w) is the force that resists a vehicle's movement due to its exposure to the wind. This force is proportional to the square of the vehicle's speed and is influenced by factors such as the vehicle's shape and cross-sectional area.

$$F_w = \frac{1}{2} \cdot \rho \cdot A_f \cdot C_D \cdot (V - V_w)^2 \quad (4)$$

where: $\rho = 1.2041$ [kg/m³] Air density of dry air at 20°C.

A_f [m²] Front area.

C_D [-] Aerodynamic drag coefficient.

V [m/s] Velocity of the vehicle.

V_{wind} [m/s] Headwind speed.

Inertial Effect (F_I) it is the force that opposes the acceleration and deceleration of a vehicle. It depends on the mass of the vehicle and the magnitude of the acceleration or deceleration. Inertial force is greater in heavier vehicles and at higher speeds.

$$F_I = M_{car} \cdot \dot{V} \quad (5)$$

where: $\dot{V}$ [m/s²] Acceleration of the vehicle.

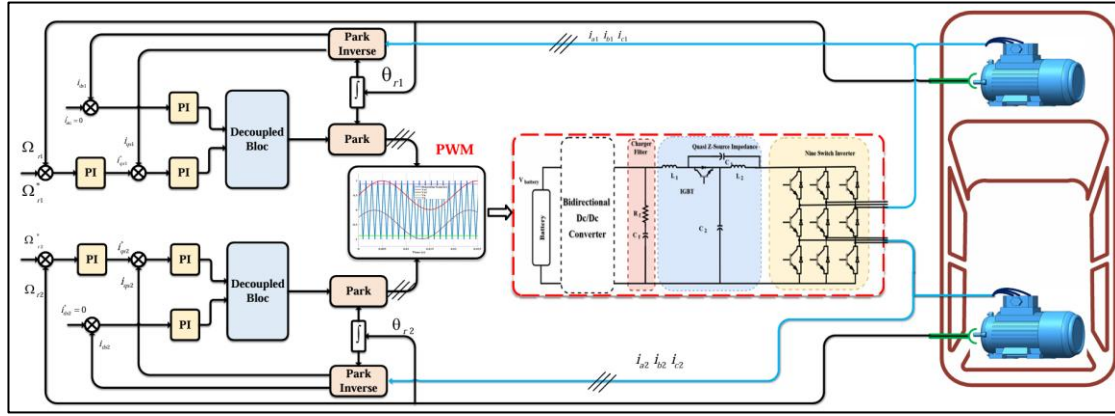


Figure 7: The general structure of the system with two motor controls.

Source: Authors, (2026).

(Figure 7) represents a vector control diagram for two permanent magnet synchronous motors powered by a single bidirectional quasi-Z-source nine-switch inverter. This system is designed to independently control the torque and speed of two PMSMs while reducing the number of power switches. Each PMSM has its own vector control loop, which includes PI controllers for the current components, decoupling blocks to cancel cross-axis interactions, Park and inverse Park transforms for reference frame conversion, and integrators to generate the rotor electrical angles. These control loops produce three-phase voltage references V_{a1}^{ref} , V_{b1}^{ref} , V_{c1}^{ref} for the front motor and V_{a2}^{ref} , V_{b2}^{ref} , V_{c2}^{ref} for the rear motor that are fed into a unified Pulse Width Modulation (PWM) block (Figure 8). The PWM modulates the nine-switch inverter, which shares three of its switches between the two motor phases, reducing the total number of switches from twelve (in two separate three-phase inverters) to nine. A quasi-Z-source network is incorporated between the DC source and the inverter to provide voltage boost capability and protection against shoot-through states, enhancing system robustness. On the output side, the inverter supplies three-phase AC voltage to each PMSM independently. Feedback from each motor, including current and speed, is used to close the control loops and ensure accurate torque and speed regulation.

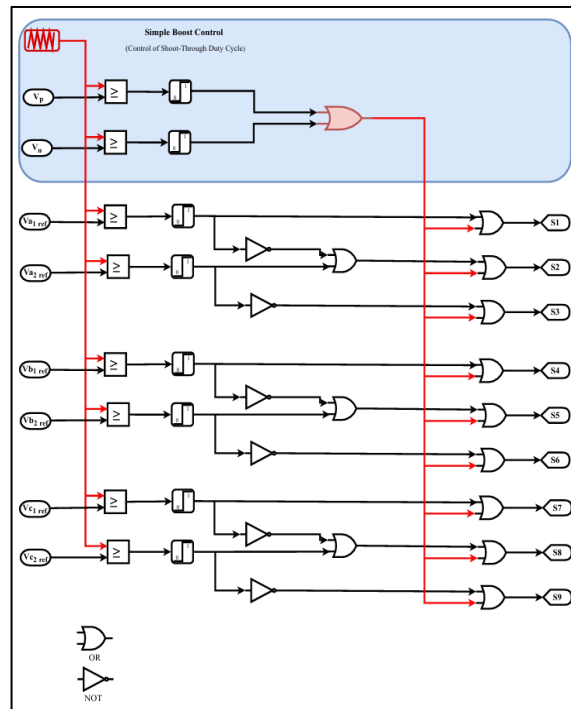


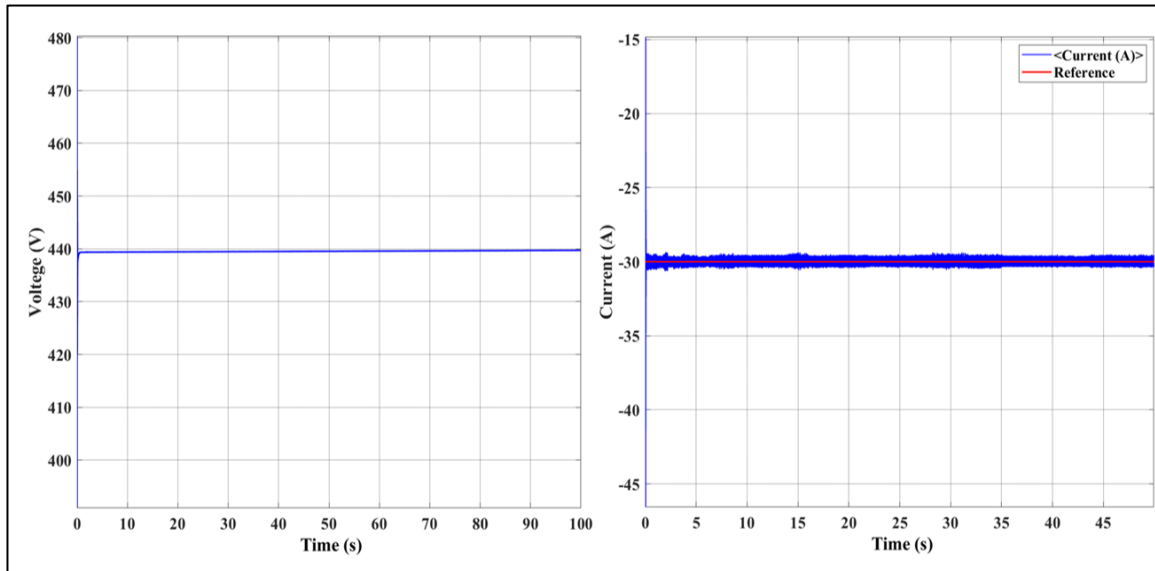
Figure 8: PWM Control.

Source: Authors, (2026).

We utilize the NEDC as our reference speed profile, which allows us to categorize the driving cycle into urban and extra-urban phases. During both phases, the inverter enables independent speed and torque control, allowing for equal torque distribution between the two motors. This approach ensures balanced operation, improves overall efficiency, and supports consistent performance across varying driving conditions.

V. RESULTS AND DISCUSSIONS

(Figure 9) represents the charging mode of the battery. Starting with the CC mode, this approach is typically used to quickly and efficiently charge the battery up to a state of charge (SOC), in our case, 90 %.



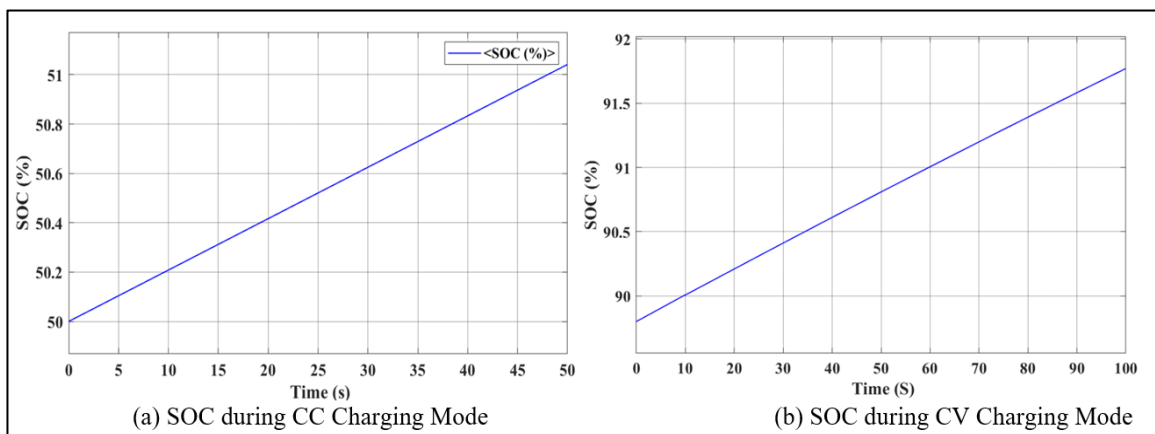
(1) Battery Voltage

(b) Battery Current

Figure 9: Constant-current Charging Mode: Battery Voltage and Current.

Source: Authors, (2026).

During the CC charging phase, the charger maintains a constant current of 30 A, (Figures 9b), which allows the battery to be charged at a relatively high rate (Figure 10a). This contributes to recharging the battery more rapidly than a pure CV charging approach. The constant current ensures the battery is charged efficiently without exposing it to high voltages, as represented in (Figure 9a), which could potentially degrade the battery over time. The charging mode was switched to CV charging once the battery reached 90 % SOC (Figure 10b).

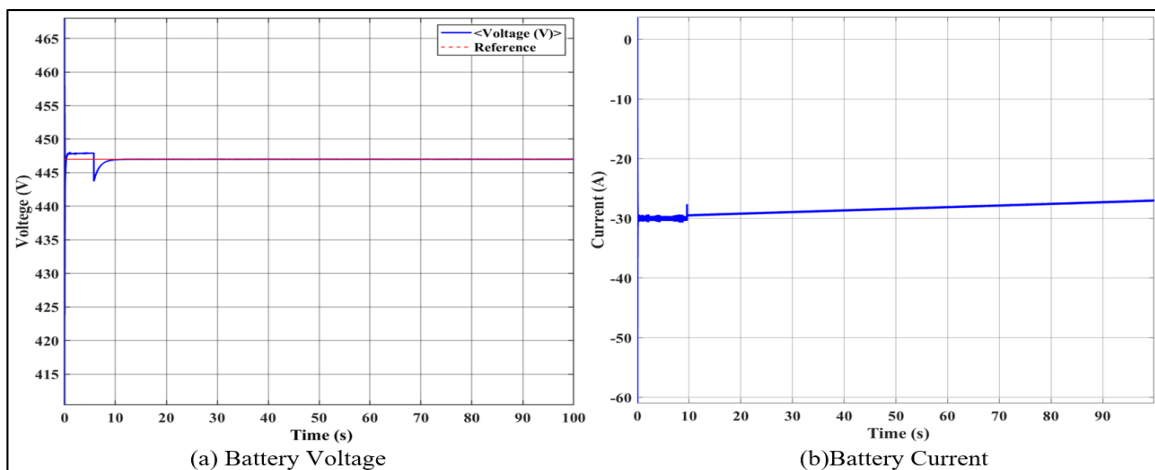


(a) SOC during CC Charging Mode

(b) SOC during CV Charging Mode

Figure 10: SOC during CC and CV Charging Mode.

Source: Authors, (2026).



(a) Battery Voltage

(b) Battery Current

Figure 11: Constant Voltage Charging Mode: Battery Voltage and Current.

Source: Authors, (2026).

During the CV charging phase, (Figure 11) the charger maintains a constant voltage (Figure 11a), while the current gradually decreases as the battery approaches full capacity, as represented in (Figure 11b). The peak shown in the (Figures 11a, 11b) represents the transition from constant current to constant voltage charging mode. This mode helps to prevent overcharging and optimize the final stages of the charging process. This strategy uses CC charging's speed and efficiency to replenish battery capacity quickly, followed by the transition to CV charging, which ensures safe completion and maintains battery health and performance. The hybrid charging strategy, which combines CC charging up to 90% SOC followed by CV charging, is often employed in electric vehicles to strike a balance between charging time, energy efficiency, and battery longevity. The torque distribution results demonstrate the algorithm's ability to allocate the required torque between the two motors effectively considering their capabilities and the overall torque requirements of the EV. The actual torque for each motor follows the reference, demonstrated in (Figures 12 and 13). To simulate real-world driving conditions in urban and extra-urban environments, we used the NEDC cycle, which provides a more realistic evaluation of vehicle behavior through the results obtained in (Figures 13, 12). The vehicle's actual speed demonstrates a high degree of concordance with the reference speed profile. This close alignment between the actual and target velocities indicates precise speed control and robust vehicle responsiveness to the prescribed driving pattern.

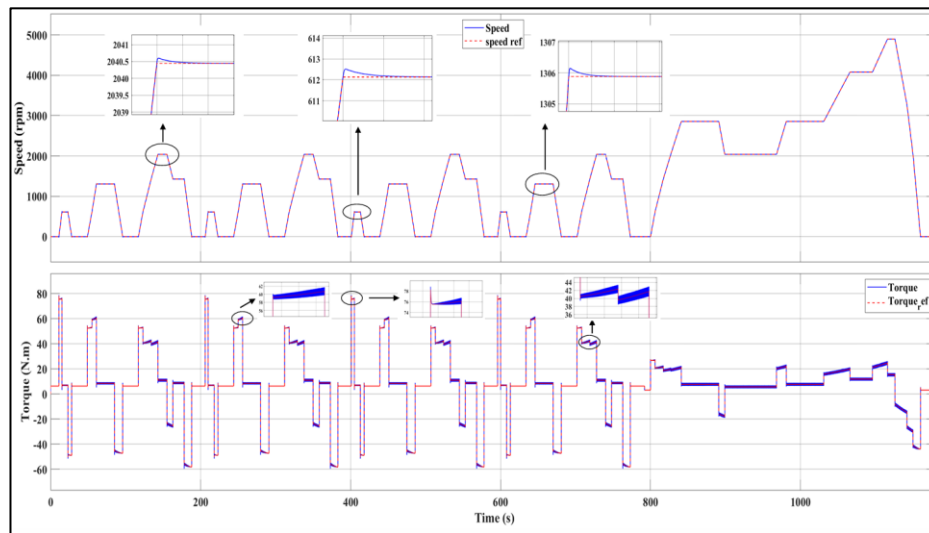


Figure 12: The speed and the torque for the front motor.

Source: Authors, (2026).

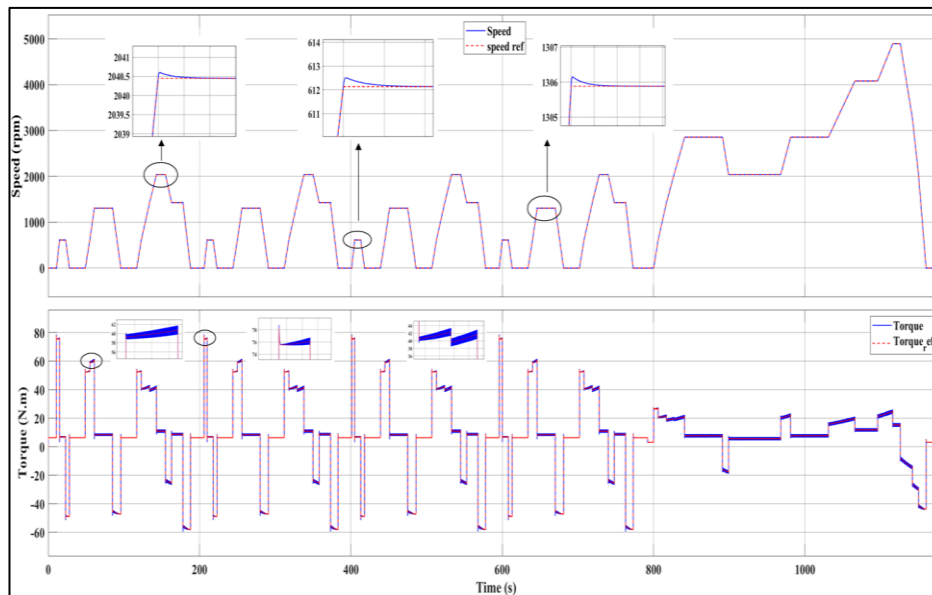


Figure 13: The speed and the torque for the rear motor.

Source: Authors, (2026).

The Figures representing the vehicle's target power profile throughout the NEDC cycle, This demand power curve indicates the instantaneous power requirements that the vehicle achieves to follow the prescribed speed and acceleration patterns accurately. By closely adhering to this demand power profile (Figures 14, 16) the vehicle demonstrates its ability to efficiently manage energy resources and respond to varying load conditions characteristic of real-world driving scenarios. The (Figures 14 and 16) display the three-phase currents (i_a , i_b , i_c) of the electric motor, which are fundamental to understanding its dynamic performance during the NEDC cycle. These currents represent the instantaneous electrical input to each of the motor's three phases, The currents exhibit a sinusoidal pattern as represented by the figure (Figures 15 and 17), with the frequency proportional to the motor's rotational speed. The varying amplitudes of i_a , i_b , and i_c reflect changes in torque demand. Higher amplitudes correspond to periods of acceleration or increased load.

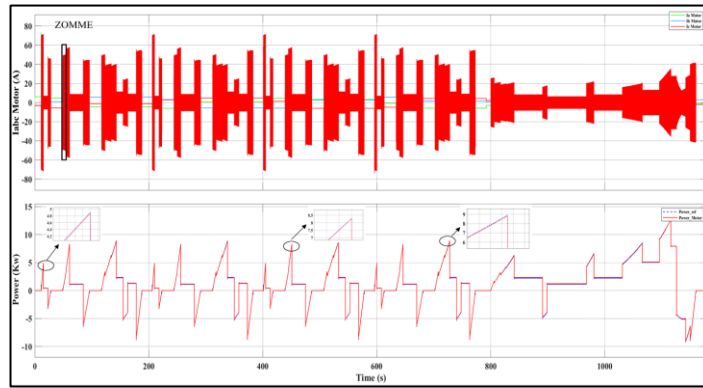


Figure 14: The current and the power for the front motor.
Source: Authors, (2026).

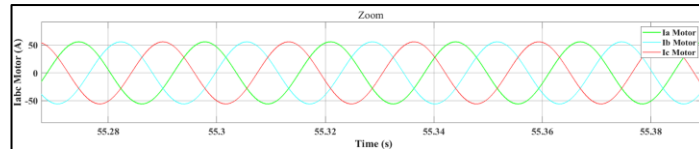


Figure 15: ZOOM current for the front motor.
Source: Authors, (2026).

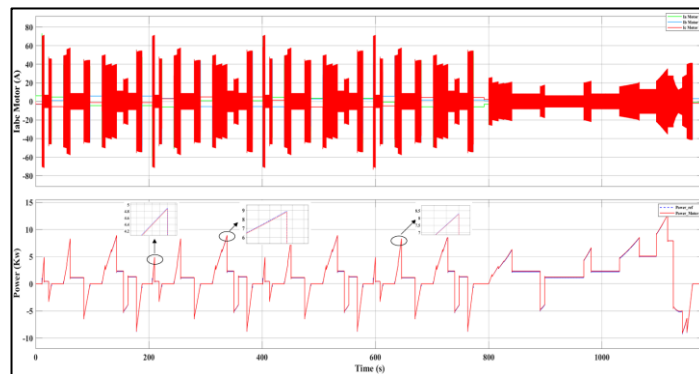


Figure 16: The current and the power for the rear motor.
Source: Authors, (2026).

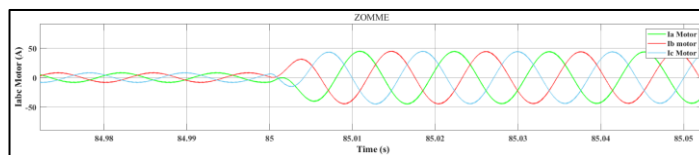


Figure 17: ZOOM current for the rear motor.
Source: Authors, (2026).

Table1: Machine and Battery Parameters.

Parameter Value	Value
Nominal torque (N.m)	$T_{nom}=400$
Nominal motor speed(rpm)	$w_{nom}=1200$
Maximum motor speed (rpm)	$w_{max}=6000$
Stator d-axis inductance (H)	$L_d=1.597 \times 10^{-3}$
Stator q-axis inductance (H)	$L_q=2.057 \times 10^{-3}$
Stator resistance per phase (Ohm)	$R_s=6.5 \times 10^{-3}$
Permanent magnet flux linkage (V.s)	$\lambda=0.1757$
Number of pole pairs	$p=4$
Rotor inertia ($Kg.m^2$)	$J=0.09$
Friction coefficient (N.m.s)	$F=0.002$
Nominal DC voltage (V)	$V_{dc,nom}=550$
Power (kW)	$P_w=50$
Voltage battery (V)	$V_b=400$
Current battery (Ah)	$I_b=40$

Source: Authors, (2026).

VI. CONCLUSIONS

This work presented a nine-switch inverter with quasi-impedance source for independently controlling dual separate motors in EVs. The main feature of the proposed configuration is to reduce the number of switching components required compared to traditional multi-motor EV configurations, with a combination of onboard charge and wireless charging capabilities. In the initial stage of this research, we demonstrated the inverter's ability to generate a continuous current to reduce stress on the components. By modifying its impedance, we gained bidirectional functionality, allowing the inverter to serve as an onboard charger. To maintain battery performance, we use the cc-cv charging method. This hybrid charging strategy is efficient in electric vehicles and balances charging time, energy efficiency, and battery longevity.

VII. AUTHOR'S CONTRIBUTION

Conceptualization: Ismail Benmiloud, Aissa Amuer, Katia Kouzi, Najib Essounbouli.

Methodology: Ismail Benmiloud, Aissa Amuer, Katia Kouzi, Najib Essounbouli.

Investigation : Ismail Benmiloud, Aissa Amuer, Katia Kouzi, Najib Essounbouli.

Discussion of results: Ismail Benmiloud, Aissa Amuer, Katia Kouzi, Najib Essounbouli.

Writing – Original Draft: Ismail Benmiloud.

Writing – Review and Editing: Aissa Amuer, Katia Kouzi, Najib Essounbouli.

Resources: Ismail Benmiloud, Aissa Amuer, Katia Kouzi, Najib Essounbouli.

Supervision:, Aissa Amuer, Katia Kouzi, Najib Essounbouli.

Approval of the final text: Ismail Benmiloud, Aissa Amuer, Katia Kouzi, Najib Essounbouli.

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