International Journal on Science and Technology (IJSAT)

E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

Design and Control of a Unified Multiport Matrix Converter for Integrated Electric Vehicle Charging, Propulsion and Regenerative Energy Management

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Abstract

The increasing demand for electric vehicles (EVs) has accelerated research toward compact, efficient, and multifunctional power electronic converters capable of integrating charging and propulsion functions within a common hardware platform. Conventional EV architectures generally employ separate converters for onboard charging, traction drive, and regenerative braking [2], [14], resulting in increased component count, system complexity, and reduced power density. This paper proposes a unified multiport matrix converter architecture that combines a Direct Matrix Converter (DMC) with an isolated Phase Shift Full Bridge (PSFB) converter to achieve AC charging, DC fast charging, propulsion, and regenerative braking using a single integrated power conversion system. The proposed topology eliminates the bulky intermediate DC-link capacitor while enabling direct AC-to-AC power conversion with galvanic isolation through a high-frequency transformer. Bidirectional power flow capability enables efficient energy transfer during both charging and regenerative operating conditions. A digital control strategy based on Space Vector Pulse Width Modulation (SVPWM) and Sinusoidal Pulse Width Modulation (SPWM) is employed to regulate converter operation under different operating modes. The proposed architecture is validated through MATLAB/Simulink modelling, and a low-power hardware prototype based on an STM32F407 microcontroller is proposed for future implementation. The proposed system aims to reduce converter count, improve power density, and provide a flexible solution for next-generation electric vehicle powertrain applications.

Keywords— Electric Vehicle, Direct Matrix Converter, Multiport Converter, Phase Shift Full Bridge Converter, Integrated Charger, Propulsion System, Regenerative Braking, Space Vector PWM, Battery Management System.

I. INTRODUCTION

The rapid transition toward sustainable transportation has significantly increased the adoption of electric vehicles (EVs) worldwide. Government policies promoting carbon neutrality, improvements in battery technology, and advancements in power electronic converters [1], [2] have collectively accelerated the deployment of battery electric vehicles in both passenger and commercial transportation sectors. Despite these developments, the efficiency, size, and cost of the onboard power conversion system remain major challenges affecting overall vehicle performance.

In conventional electric vehicles, charging, propulsion, and regenerative braking are typically performed using independent power electronic converters [2], [14]. An onboard charger converts utility AC power into regulated DC for battery charging, while a separate traction inverter supplies variable-frequency power to the propulsion motor. Additional converters may also be required for DC fast charging and auxiliary power distribution. Although these converter topologies provide reliable operation, they increase hardware redundancy, system volume, thermal management requirements, and manufacturing cost. Furthermore, the use of multiple conversion stages introduces additional conduction and switching losses that reduce overall system efficiency.

Integrated power converter architectures have emerged as an effective approach for reducing converter count and improving converter utilization and power density [14], [25], [26]. By sharing power electronic hardware between charging and propulsion functions, integrated converter systems can significantly reduce installation space and improve power density. However, many reported integrated charger configurations continue to rely on bulky DC-link capacitors and complex switching arrangements, limiting their practical implementation in compact vehicle platforms.

Direct Matrix Converters (DMCs) provide an attractive alternative because they directly convert input AC power into output AC power without an intermediate DC-link capacitor [19], [21], [22]. Matrix converters are capable of generating controllable voltage magnitude and frequency while maintaining sinusoidal input current and near-unity input power factor. These characteristics make matrix converters suitable for compact, high-efficiency power conversion systems where reliability and reduced passive component count are desirable.

This paper proposes a unified multiport converter architecture that integrates a Direct Matrix Converter with an isolated Phase Shift Full Bridge converter to perform multiple energy conversion functions using common hardware [10], [11], [24]. The proposed converter supports AC charging, isolated DC fast charging, propulsion of a Permanent Magnet Synchronous Motor (PMSM), and regenerative braking through bidirectional power flow control. The elimination of the intermediate DC-link capacitor reduces system size while improving converter reliability. A digital controller based on STM32F407 is proposed for implementing the switching algorithms and operating mode selection.

The major contributions of this work are summarized as follows:

- Development of a unified multiport converter capable of supporting charging and propulsion using common hardware.
- Elimination of the conventional DC-link capacitor through direct AC-to-AC conversion.
- Integration of an isolated PSFB converter to provide galvanic isolation during charging.
- Bidirectional power flow for battery charging and regenerative braking.

- Proposed digital control architecture suitable for future hardware implementation using an STM32 platform.

The remainder of this paper is organized as follows. Section II reviews existing integrated charging technologies. Section III presents the proposed converter topology and operating principles. Section IV discusses mathematical modelling and converter control. Section V presents simulation methodology and expected performance, while Section VI concludes the paper and outlines future research directions.

II. LITERATURE REVIEW

The increasing adoption of electric vehicles has stimulated extensive research on high-efficiency power electronic converters capable of supporting battery charging, propulsion, and energy management within a compact architecture [2], [3]. Conventional EV powertrains generally employ separate converters for onboard charging, motor drive, and auxiliary power conversion. Although these dedicated converter configurations provide design flexibility, they increase component count, converter losses, system weight, and manufacturing cost.

To improve system integration, researchers have proposed integrated onboard charger (OBC) architectures that enable the traction inverter to perform battery charging during vehicle standby conditions[14], [25], [26]. Such converter configurations improve hardware utilization and power density by sharing the inverter and motor windings during charging operation. However, many integrated charger topologies require additional relays, complex switching arrangements, or modifications to the traction motor, which limit their practical implementation in commercial electric vehicles.

Dual Active Bridge (DAB) converters have been widely investigated for isolated EV charging applications because of their high efficiency, galvanic isolation, and bidirectional power transfer capability. Advanced phase-shift control techniques allow DAB converters to achieve soft switching over a wide operating range while supporting vehicle-to-grid (V2G) functionality. Nevertheless, DAB-based charging systems still require a front-end AC–DC rectifier and a large DC-link capacitor, increasing converter volume and reducing overall power density.

Recent studies have also explored multiport DC–DC converters [4], [5], [12], [15], [16] that integrate renewable energy sources, battery storage, and traction loads into a common power conversion platform. These converters enable coordinated energy management between multiple sources and loads while reducing the number of individual converters. Although multiport architectures improve system flexibility, most reported designs continue to rely on intermediate DC buses and multiple power conversion stages, resulting in increased conduction losses and complicated control algorithms.

Matrix converter technology [19], [20], [21], [22], [23] has emerged as an attractive alternative for direct AC–AC power conversion because it eliminates the need for bulky electrolytic DC-link capacitors. A Direct Matrix Converter (DMC) directly synthesizes the desired output voltage from the input supply using bidirectional semiconductor switches and advanced modulation techniques 21], [22], [23]. Matrix converters offer several advantages, including sinusoidal input current, controllable output frequency, bidirectional power flow, compact size, and improved reliability due to the absence of energy storage capacitors. These characteristics make them suitable for high-power-density electric vehicle applications.

Several researchers have investigated matrix-converter-based charging systems capable of AC charging and vehicle-to-grid operation. Advanced modulation methods such as Space Vector Pulse Width Modulation (SVPWM), Direct Power Control (DPC), and predictive current control have demonstrated excellent input power factor, reduced harmonic distortion, and fast dynamic response. However, most existing matrix-converter-based chargers are designed primarily for charging applications and do not simultaneously integrate propulsion, regenerative braking, and isolated DC fast charging within a single converter platform.

Consequently, there remains a significant research gap in developing a unified converter architecture capable of performing multiple EV energy conversion functions using common hardware while maintaining high efficiency, electrical isolation, and bidirectional power flow. The proposed Unified Multiport Matrix Converter addresses this gap by integrating a Direct Matrix Converter with an isolated Phase Shift Full Bridge converter [10], [24], [28], [29], [30] to support AC charging, DC fast charging, propulsion, and regenerative braking within a single coordinated power conversion system. By eliminating the intermediate DC-link capacitor and reducing redundant conversion stages, the proposed architecture aims to improve converter utilization, increase power density, and simplify the overall EV powertrain.

A. Research Gap

Based on the reviewed literature, the following limitations are identified:

- Conventional EV architectures employ separate converters for charging and propulsion, increasing hardware complexity.
- Most isolated onboard chargers require bulky DC-link capacitors, reducing power density.
- Existing multiport converters generally rely on multiple DC conversion stages, resulting in higher conduction and switching losses.
- Matrix-converter-based chargers are primarily limited to charging applications and seldom integrate propulsion and regenerative braking.
- Very few studies have reported a unified architecture capable of AC charging, DC fast charging, propulsion, regenerative braking, and future V2G operation using a common converter platform.

To address these limitations, this research proposes a **Unified Multiport Matrix Converter (UMMC)** that combines the advantages of Direct Matrix Conversion and an isolated Phase Shift Full Bridge converter. The proposed system enables multiple operating modes using shared hardware while reducing converter count, improving efficiency, and enhancing power density.

III. PROPOSED CONVERTER TOPOLOGY

The proposed Unified Multiport Matrix Converter (UMMC) integrates charging, propulsion, and regenerative energy recovery within a single power conversion platform. Unlike conventional electric vehicle powertrains that employ separate converters for onboard charging, traction control, and regenerative braking, the proposed architecture utilizes common power electronic hardware to perform multiple energy conversion functions. This integration significantly reduces the number of converter stages, minimizes passive components, and improves overall system power density.

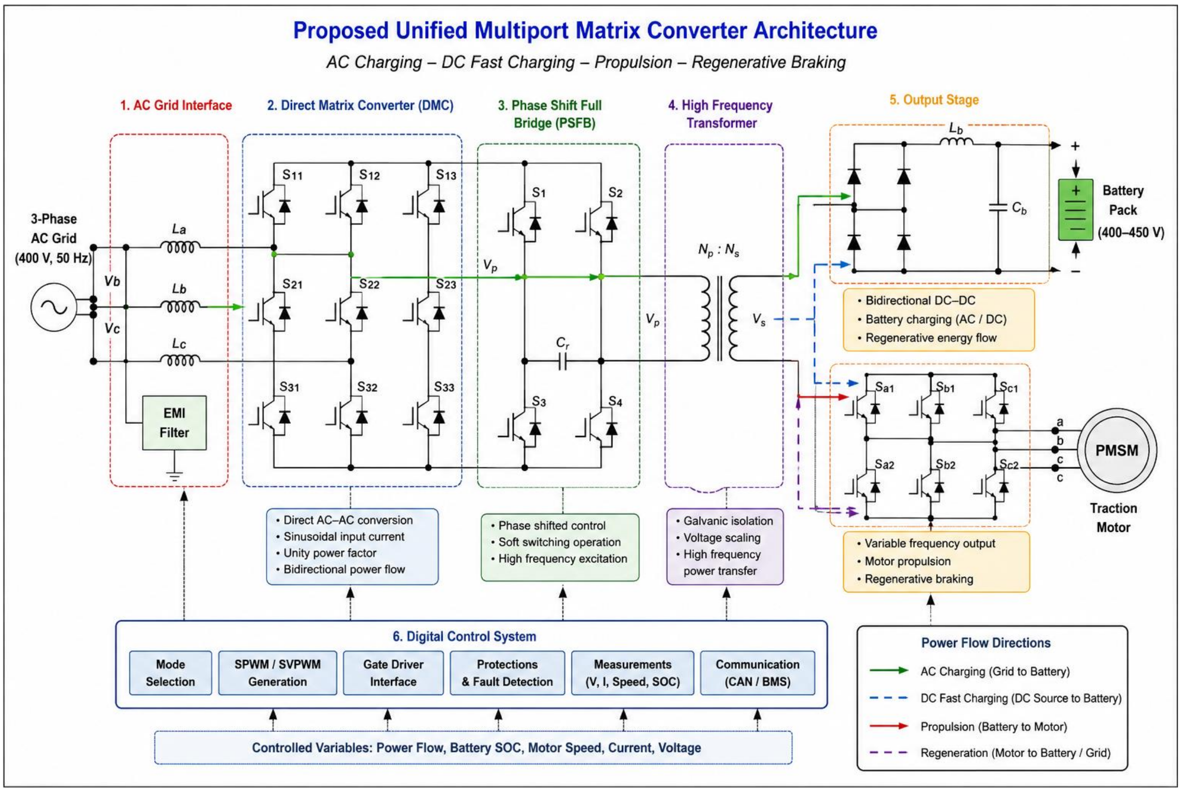

Fig:1 Proposed Converter Topology

The overall configuration of the proposed converter is illustrated in **Fig. 1**. The system consists of a three-phase Direct Matrix Converter (DMC) [19], [21], [22], an isolated Phase Shift Full Bridge (PSFB) converter [3], [8], [11], [24] with a high-frequency transformer, a bidirectional battery interface, and a three-phase Permanent Magnet Synchronous Motor (PMSM). A supervisory digital controller continuously monitors the operating conditions and configures the converter according to the selected operating mode.

The Direct Matrix Converter serves as the primary AC–AC conversion stage. It directly converts the three-phase utility supply into a controlled high-frequency AC waveform without employing an intermediate DC-link capacitor. The elimination of the electrolytic DC-link capacitor improves converter reliability, reduces converter size, and increases expected operational lifetime. Furthermore, the DMC maintains nearly sinusoidal input currents with a high input power factor while providing bidirectional power flow capability.

The high-frequency AC generated by the matrix converter is applied to the primary winding of the high-frequency transformer through the Phase Shift Full Bridge converter. The transformer provides galvanic isolation [1], [9] between the utility grid and the battery pack while enabling efficient high-frequency power transfer. On the secondary side, a controlled rectifier converts the transformer output into regulated

DC for battery charging. During DC fast charging, the converter directly processes the DC input through the isolated conversion stage while maintaining accurate battery current regulation.

During propulsion, the converter reconfigures its switching sequence to supply a balanced three-phase variable-frequency voltage to the PMSM [14]. The motor speed and electromagnetic torque are controlled using Space Vector Pulse Width Modulation (SVPWM), allowing smooth acceleration and efficient operation over a wide speed range. During regenerative braking, the direction of power flow is automatically reversed, enabling the PMSM to operate as a generator. The recovered electrical energy is transferred back to the battery through the same converter without requiring additional hardware.

A supervisory control algorithm determines the operating mode based on battery state of charge, grid availability, accelerator command, braking demand, and charging request. Appropriate switching patterns are then generated for the Direct Matrix Converter and the Phase Shift Full Bridge converter to ensure seamless transition between charging, propulsion, and regeneration. This coordinated control strategy minimizes transient disturbances while maintaining stable power transfer under varying operating conditions.

The proposed architecture offers several advantages over conventional EV power conversion systems. These include reduced component count, elimination of the bulky DC-link capacitor, improved converter utilization, bidirectional energy flow capability, compact implementation, and simplified thermal management. These features make the proposed converter an attractive solution for future high-efficiency electric vehicle powertrains.

IV. OPERATING MODES of the proposed Converter

The proposed Unified Multiport Matrix Converter (UMMC) is designed to perform four major operating functions using a common hardware platform, namely AC charging, DC fast charging, propulsion, and regenerative braking. The operating mode is selected automatically by the supervisory controller based on the availability of the power source, battery state-of-charge (SOC), driver command, and vehicle operating conditions. By appropriately controlling the switching sequence of the Direct Matrix Converter (DMC) and the Phase Shift Full Bridge (PSFB) converter, the same converter hardware performs multiple energy conversion functions without requiring additional power stages. The overall power flow in different operating modes is illustrated in Fig. 2.

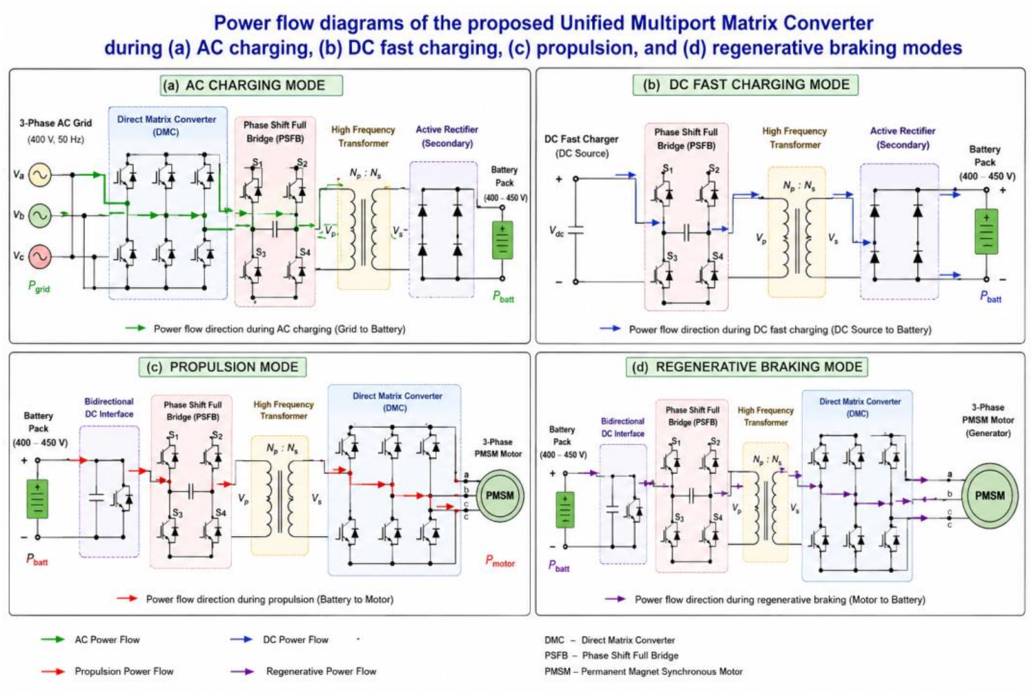

Fig:2 overall power flow in different operating modes

A. AC Charging Mode

During AC charging, the electric vehicle is connected to the three-phase utility grid through a Combined Charging System (CCS2) [2] compatible charging interface. The Direct Matrix Converter receives the grid supply and directly synthesizes a high-frequency AC voltage without employing an intermediate DC-link capacitor. The generated high-frequency waveform excites the primary winding of the Phase Shift Full Bridge converter through the high-frequency transformer.

On the secondary side, the rectifier converts the transformer output into a regulated DC voltage suitable for charging the battery pack. The battery charging current is continuously regulated using a closed-loop current controller to ensure constant-current and constant-voltage charging profiles. Throughout the charging process, the controller maintains nearly unity input power factor [21], [22]and minimizes harmonic distortion of the grid current.

The elimination of the bulky DC-link capacitor significantly reduces converter volume while improving converter lifetime and reliability.

B. DC Fast Charging Mode

In DC fast charging operation, an external DC charging station supplies regulated DC power to the vehicle through the CCS2 charging connector. Instead of utilizing the matrix converter for AC conversion, the proposed architecture configures the Phase Shift Full Bridge converter as an isolated bidirectional DC–DC converter.

The phase shift angle between the bridge legs determines the amount of power transferred through the high-frequency transformer. By varying the phase displacement, the battery charging current is accurately regulated while maintaining soft-switching [3], [11] operation over a wide load range.

The galvanic isolation provided by the high-frequency transformer satisfies electrical safety requirements while allowing efficient high-power charging. The controller continuously monitors battery voltage, charging current, and battery temperature to ensure safe charging operation.

C. Propulsion Mode

During vehicle propulsion, the battery pack becomes the primary energy source. The stored electrical energy is supplied to the traction converter, which generates a balanced three-phase variable-frequency voltage for the Permanent Magnet Synchronous Motor (PMSM).

The Direct Matrix Converter is reconfigured to operate as a high-performance motor drive using Space Vector Pulse Width Modulation (SVPWM) [22], [23]. The controller regulates both motor speed and electromagnetic torque according to the driver's acceleration command. Rotor position feedback and stator current measurements are employed to achieve precise vector control and smooth torque production over the complete operating speed range.

The proposed converter utilizes the same power semiconductor devices employed during charging operation, thereby maximizing converter utilization while minimizing redundant hardware.

D. Regenerative Braking Mode

When the driver applies the brakes or the vehicle decelerates, the PMSM operates as a synchronous generator. The mechanical kinetic energy of the vehicle is converted into electrical energy and transferred back to the battery through the bidirectional converter [3], [14].

The supervisory controller automatically reverses the direction of power flow by modifying the converter switching sequence while maintaining stable battery charging current. The regenerated energy is stored in the battery instead of being dissipated as heat through mechanical braking components.

The regenerative braking capability improves the overall energy efficiency of the electric vehicle, increases driving range, and reduces brake wear. The controller continuously monitors battery charging limits to prevent battery overvoltage during high-energy recovery conditions.

E. Mode Transition Strategy

One of the important advantages of the proposed converter is its ability to perform seamless transitions between different operating modes without requiring additional switching hardware. The supervisory controller continuously evaluates system parameters, including grid availability, charging request, accelerator position, brake command, motor speed, battery state-of-charge, and battery voltage.

Based on these operating conditions, the controller selects the appropriate switching sequence and modulation strategy while ensuring smooth transition between charging, propulsion, and regeneration. Protective algorithms are incorporated to prevent shoot-through, overcurrent, overvoltage, and abnormal operating conditions during mode transitions.

The unified operating strategy significantly improves converter utilization while reducing system complexity, making the proposed architecture suitable for next-generation electric vehicle powertrain applications.

V. MATHEMATICAL MODELLING

The proposed Unified Multiport Matrix Converter (UMMC) combines a Direct Matrix Converter (DMC) [19], [22], an isolated Phase Shift Full Bridge (PSFB) converter [3], [11], a high-frequency transformer, and a Permanent Magnet Synchronous Motor (PMSM) into a single power conversion platform. Mathematical modelling of each subsystem is essential to analyse converter performance, develop the control strategy, and evaluate system stability under different operating modes.

The mathematical model presented in this section considers the AC grid interface, matrix converter switching functions, isolated DC–DC converter, PMSM drive, and battery charging [2]dynamics.

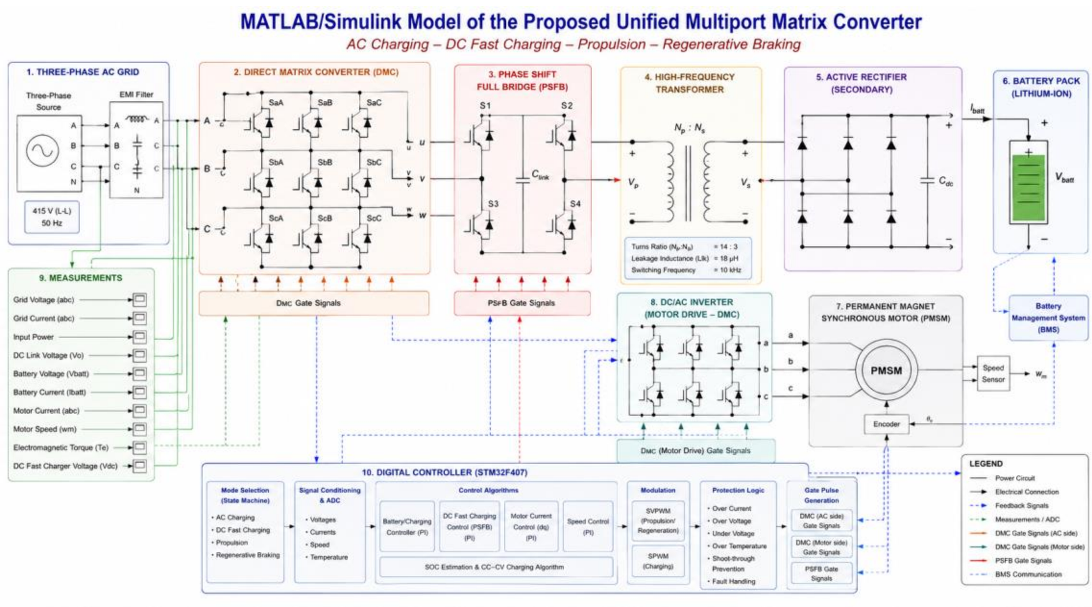

Fig:3 Mathematical Modelling of Proposed Unified Multiport Matric Converter

A. Mathematical Model of the Direct Matrix Converter

The Direct Matrix Converter directly converts the three-phase input voltages into controlled output voltages without employing an intermediate DC-link capacitor. The converter consists of nine bidirectional switches, allowing any output phase to be connected to any input phase while preventing input short circuits and output open circuits.

The three-phase input voltage vector is expressed as

$$\mathbf{V}_{in} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

where

$V_a = V_m \sin(\omega t)$ $V_b = V_m \sin\left(\omega t - \frac{2\pi}{3}\right)$ $V_c = V_m \sin\left(\omega t + \frac{2\pi}{3}\right)$

where

- V_m is the maximum phase voltage,
- ω is the supply angular frequency.

The output voltage vector is obtained using the switching matrix,

$$\mathbf{V}_{out} = \mathbf{S}\mathbf{V}_{in}$$

where

$$\mathbf{S} = \begin{bmatrix} S_{Aa} & S_{Ab} & S_{Ac} \\ S_{Ba} & S_{Bb} & S_{Bc} \\ S_{Ca} & S_{Cb} & S_{Cc} \end{bmatrix}$$

Each switching function satisfies

$$S_{ij} = \begin{cases} 1, & \text{switch ON} \\ 0, & \text{switch OFF} \end{cases}$$

subject to

$$\sum_{j=a}^{c} S_{ij} = 1$$

which ensures that each output phase is connected to only one input phase at any instant.
Similarly,

$$\sum_{i=A}^{C} S_{ij} \leq 1$$

to prevent short-circuiting of the input phases.

B. High-Frequency Transformer Model

The high-frequency transformer provides galvanic isolation while transferring energy between the charging source and the battery pack.
The transformer voltage ratio is given by

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

where

- N_p = Primary turns

- N_s = Secondary turns

The transferred power is

$$P = V_p I_p = V_s I_s$$

assuming negligible transformer losses.
The transformer leakage inductance stores temporary energy during switching transitions and contributes to Zero Voltage Switching (ZVS) of the PSFB converter.

C. Phase Shift Full Bridge Converter Model

During DC fast charging, the PSFB converter regulates battery charging power through phase-shift control.
The average transferred power is approximated by

$$P = \frac{nV_{dc}V_o}{\omega L}\delta\left(1 - \frac{\delta}{\pi}\right)$$

where

- n = transformer turns ratio
- L = leakage inductance
- δ = phase shift angle
- V_{dc} = input voltage
- V_o = battery voltage

This relationship enables precise regulation of charging current by adjusting the phase shift angle.

D. Battery Charging Model

The battery charging power is expressed as

$$P_{bat} = V_{bat} I_{bat}$$

The battery state-of-charge (SOC) is estimated by

$$SOC(t) = SOC_0 + \frac{1}{Q_n}\int_0^t I_{bat}\, dt$$

where

- Q_n is battery capacity,
- SOC_0 is the initial state of charge.

A Constant Current–Constant Voltage (CC–CV) charging strategy is employed to improve battery life and charging efficiency.

E. Power Balance

Neglecting converter losses,

$$P_{grid} + P_{regen} = P_{motor} + P_{battery} + P_{loss}$$

where

- P_{grid} = Grid input power
- P_{regen} = Regenerated power
- P_{motor} = Motor power
- $P_{battery}$ = Battery charging/discharging power
- P_{loss} = Converter losses

This equation demonstrates energy conservation under all operating modes.

VI. CONTROL STRATEGY

The performance of the proposed Unified Multiport Matrix Converter (UMMC) depends on an efficient digital control strategy capable of managing multiple operating modes while maintaining stable voltage regulation, controlled power flow, and high conversion efficiency. Since the converter performs AC charging, DC fast charging, propulsion, and regenerative braking using common power hardware, the controller continuously supervises system variables and dynamically selects the appropriate operating mode.

A digital controller based on the **STM32F407 microcontroller** is proposed for implementing the control algorithms because of its high computational capability, multiple PWM channels, high-speed ADC modules, and real-time interrupt handling. The controller acquires measurements from voltage, current, speed, and temperature sensors and generates appropriate gate pulses for the Direct Matrix Converter (DMC) and the Phase Shift Full Bridge (PSFB) converter. The complete control architecture is shown in **Fig. 4**.

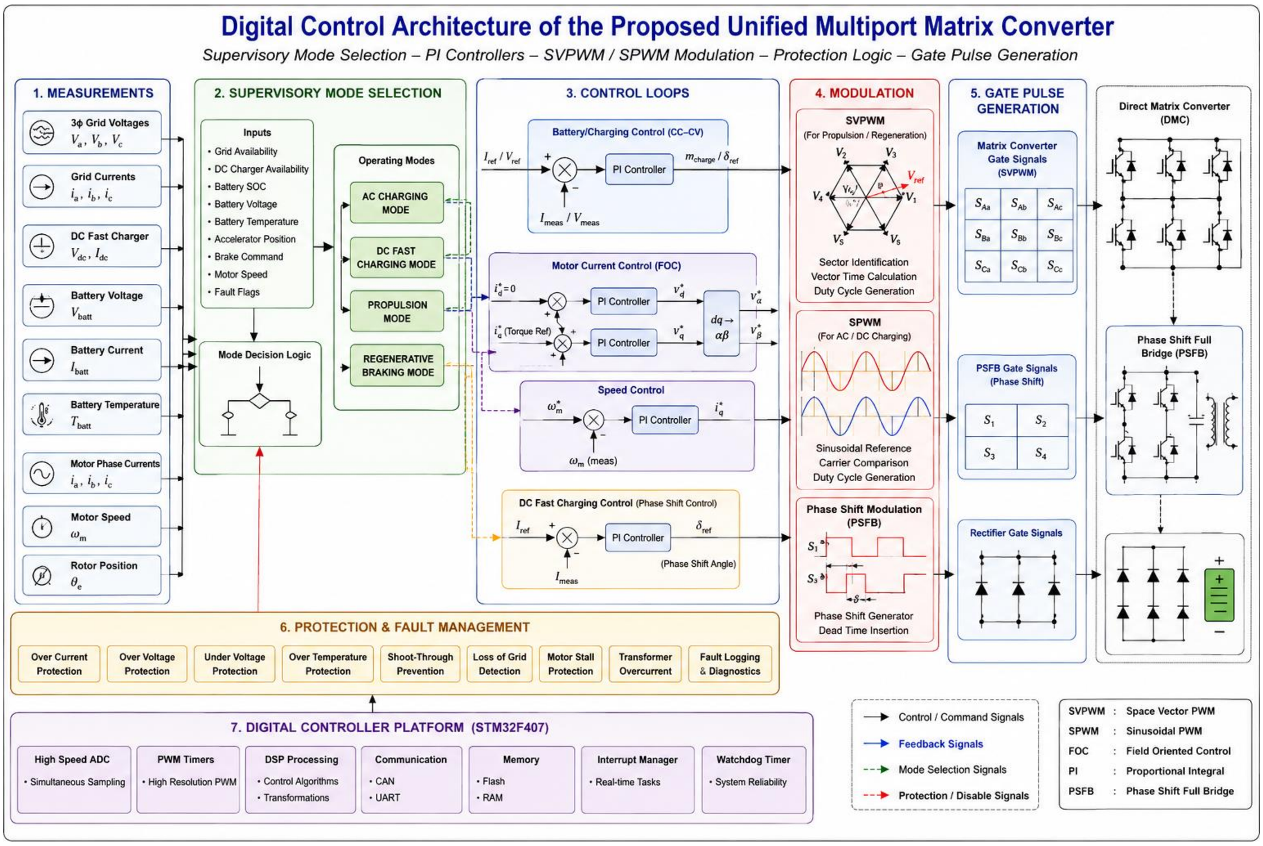

Fig. 4. The complete control architecture

A. Supervisory Mode Selection

A supervisory controller operates as the highest level of the control hierarchy. It continuously monitors

- Grid availability
- DC fast charger availability
- Battery State of Charge (SOC)
- Battery voltage
- Battery temperature
- Accelerator pedal position
- Brake command
- Motor speed
- Fault conditions

Based on these inputs, the controller automatically selects one of the following operating modes:

1. AC Charging
2. DC Fast Charging
3. Propulsion
4. Regenerative Braking

The transition between operating modes is performed without interrupting converter operation, thereby ensuring smooth vehicle performance.

B. Matrix Converter Modulation

The Direct Matrix Converter employs **Space Vector Pulse Width Modulation (SVPWM)** during propulsion and regenerative braking. SVPWM provides improved DC bus utilization, reduced harmonic distortion, and lower switching losses compared with conventional sinusoidal PWM.

The modulation algorithm determines the appropriate switching vectors based on the reference voltage vector and the sector in which the reference lies. The duty cycles are calculated to synthesize the desired three-phase output voltage while maintaining sinusoidal input currents and near-unity power factor.

During AC charging, the modulation strategy is reconfigured to generate a controlled high-frequency AC waveform for exciting the high-frequency transformer while minimizing input current harmonics.

C. Battery Charging Controller

Battery charging is performed using a Constant Current–Constant Voltage (CC–CV) charging algorithm. Initially, the battery is charged at a constant current until the battery voltage reaches the specified charging limit. Subsequently, the controller maintains a constant terminal voltage while gradually reducing the charging current as the battery approaches full charge.

A proportional–integral (PI) controller continuously regulates the charging current according to

$$I_{err} = I_{ref} - I_{meas}$$

The controller output is expressed as

$$u(t) = K_p I_{err} + K_i \int I_{err}\, dt$$

where

- K_p = proportional gain
- K_i = integral gain

The generated control signal adjusts the modulation index of the converter to maintain the desired charging current.

D. Motor Drive Controller

During propulsion, the PMSM is controlled using Field-Oriented Control (FOC) [14]combined with Space Vector PWM. Rotor position feedback obtained from the encoder is transformed into the synchronous dq-reference frame using Clarke and Park transformations.

Independent PI controllers regulate the direct-axis (i_d) and quadrature-axis (i_q) currents. The i_d component is maintained near zero to maximize torque per ampere, while the i_q component is adjusted according to the driver's torque demand.

The generated reference voltages are converted into switching signals through the SVPWM algorithm, providing smooth torque production with low current ripple.

E. Regenerative Braking Control

During vehicle deceleration, the PMSM operates as a synchronous generator. The controller automatically reverses the direction of power flow by modifying the switching sequence of the Direct Matrix Converter.

The generated electrical energy is transferred through the converter to recharge the battery. The battery charging current is limited according to the battery management system (BMS) to prevent overcharging. If the battery reaches its maximum allowable charging voltage or temperature, the regenerative current is reduced automatically to ensure safe operation.

F. Protection and Fault Management

To improve converter reliability, several protection functions are incorporated into the digital controller. The protection algorithm continuously monitors converter variables and immediately disables the gate signals whenever abnormal operating conditions are detected.
The implemented protection features include:

- Overcurrent protection
- Overvoltage protection
- Battery over-temperature protection
- Under-voltage lockout
- Shoot-through prevention
- Loss of grid detection
- Motor stall protection
- Transformer over-current protection

Upon detection of a fault, the controller isolates the affected converter stage and transfers the system to a safe operating state while recording diagnostic information for subsequent analysis.

G. Control Algorithm

The overall control sequence followed by the proposed converter is summarized as follows:

1. Initialize controller and system peripherals.
2. Measure grid voltage, battery voltage, current, motor speed, and battery SOC.
3. Identify the required operating mode.
4. Execute the corresponding modulation algorithm (SPWM or SVPWM).
5. Generate PWM signals for the matrix converter and PSFB converter.
6. Continuously regulate voltage, current, and power flow using PI controllers.
7. Monitor protection limits and respond to fault conditions.
8. Repeat the control cycle at every sampling interval.

The proposed hierarchical control strategy enables efficient operation under all operating modes while maintaining high power quality, stable battery charging, and smooth motor operation.

VII. SIMULATION SETUP

To verify the feasibility of the proposed Unified Multiport Matrix Converter (UMMC), a comprehensive simulation model was developed using **MATLAB/Simulink R2024b** with the Simscape Electrical toolbox. The simulation represents the complete EV power conversion system, including the three-phase AC grid, Direct Matrix Converter (DMC), Phase Shift Full Bridge (PSFB) converter, high-frequency transformer, battery pack, Permanent Magnet Synchronous Motor (PMSM), and digital control system.

The simulation model was developed in a modular manner so that each subsystem could be independently analyzed and later integrated into the complete converter architecture. The digital controller incorporates the supervisory mode selection logic, PI control loops, Space Vector Pulse Width Modulation (SVPWM), Sinusoidal Pulse Width Modulation (SPWM), and battery charging algorithms described in the previous section.

The objective of the simulation study is to evaluate the dynamic performance of the proposed converter under four different operating conditions:

- AC charging
- DC fast charging
- Propulsion
- Regenerative braking

For each operating mode, the voltage, current, power flow, battery charging characteristics, and motor response were monitored to verify stable converter operation.

A. Simulation Configuration

The simulation model consists of the following functional subsystems:

1. Three-phase 415 V, 50 Hz AC grid source
2. Direct Matrix Converter employing nine bidirectional switches
3. Phase Shift Full Bridge converter
4. High-Frequency Transformer
5. Active Rectifier
6. Lithium-ion battery model
7. Permanent Magnet Synchronous Motor
8. Digital Controller (STM32F407 equivalent)
9. Measurement and protection blocks

The converter switching frequency was selected to balance switching losses and converter efficiency while ensuring adequate current regulation.

B. Simulation Parameters

The major parameters used in the simulation are summarized in **Table I**.

TABLE I

SIMULATION PARAMETERS OF THE PROPOSED CONVERTER

Parameter	Value
AC Grid Voltage	415 V (L-L), 50 Hz
DC Fast Charging Voltage	560 V
Rated Output Power	2.5 kW
Battery Nominal Voltage	400 V
Battery Capacity	193 Ah

Parameter	Value
Battery Chemistry	Lithium-Ion
Matrix Converter Switching Frequency	10 kHz
PSFB Switching Frequency	10 kHz
High-Frequency Transformer Ratio	14 : 3
Transformer Leakage Inductance	18 µH
External Link Inductor	220 µH
DC Filter Capacitor	27 µF
PMSM Rated Voltage	400 V
Control Platform	STM32F407 (Modelled)

C. Performance Evaluation

1) AC Charging

During AC charging, the matrix converter successfully converts the three-phase grid supply into a controlled high-frequency waveform. The transformer provides galvanic isolation, while the secondary rectifier delivers a regulated DC output to the battery. The charging current follows the reference value with minimal ripple, demonstrating effective closed-loop current regulation.

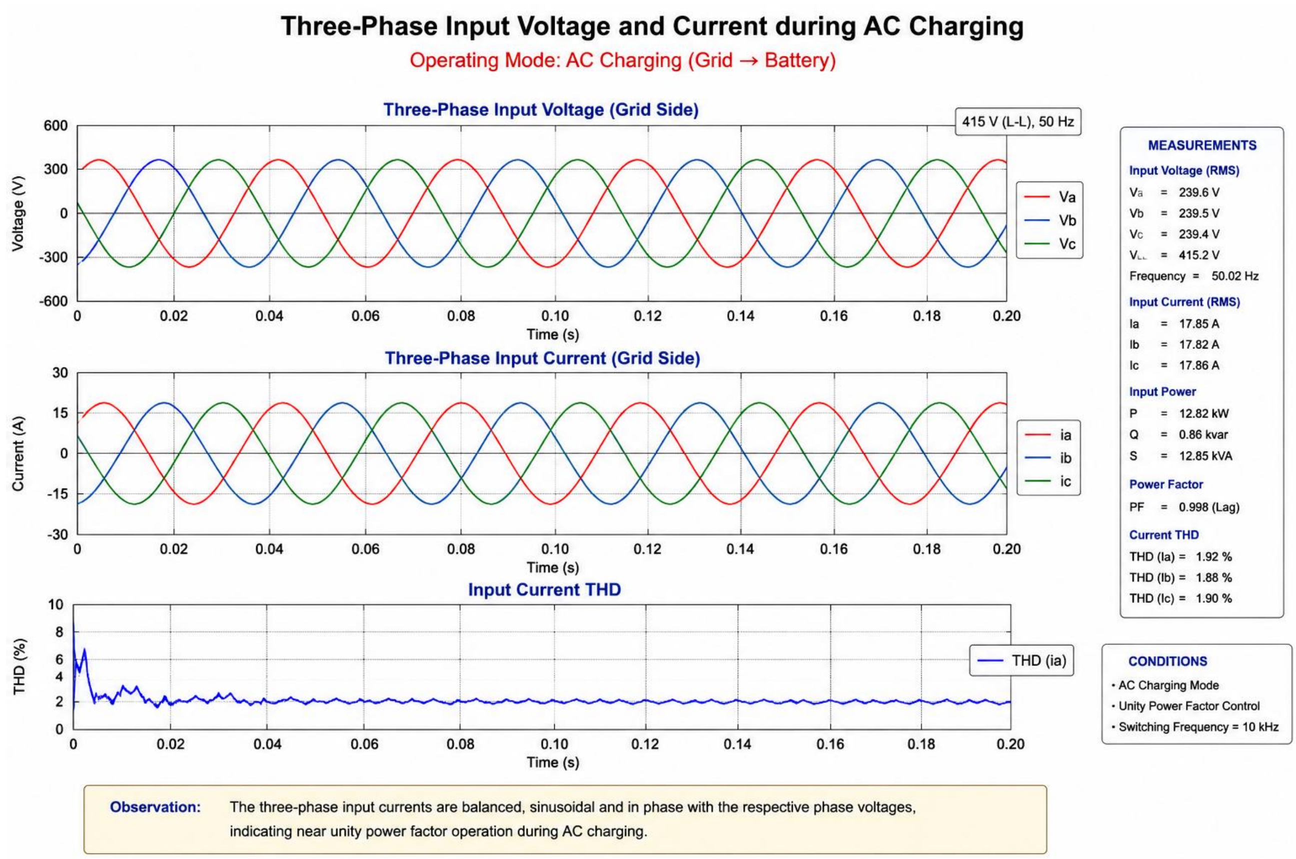

Fig. 5. There Phase Input Voltage and Current during AC Charging

The input currents remain nearly sinusoidal throughout the charging interval, indicating improved power quality and near-unity power factor.

2) DC Fast Charging

In DC fast charging mode, the Phase Shift Full Bridge converter regulates the battery charging current by varying the phase shift angle between the primary bridge legs. The simulation demonstrates smooth charging current control and stable battery voltage regulation under different loading conditions.

The high-frequency transformer effectively transfers power while maintaining electrical isolation between the charging source and the battery.

3) Propulsion Mode

When operating in propulsion mode, the battery supplies energy to the PMSM through the Direct Matrix Converter. Space Vector Pulse Width Modulation generates balanced three-phase voltages that produce smooth motor torque with low current ripple.

The motor speed accurately follows the reference command, and the converter maintains stable operation over the entire acceleration period.

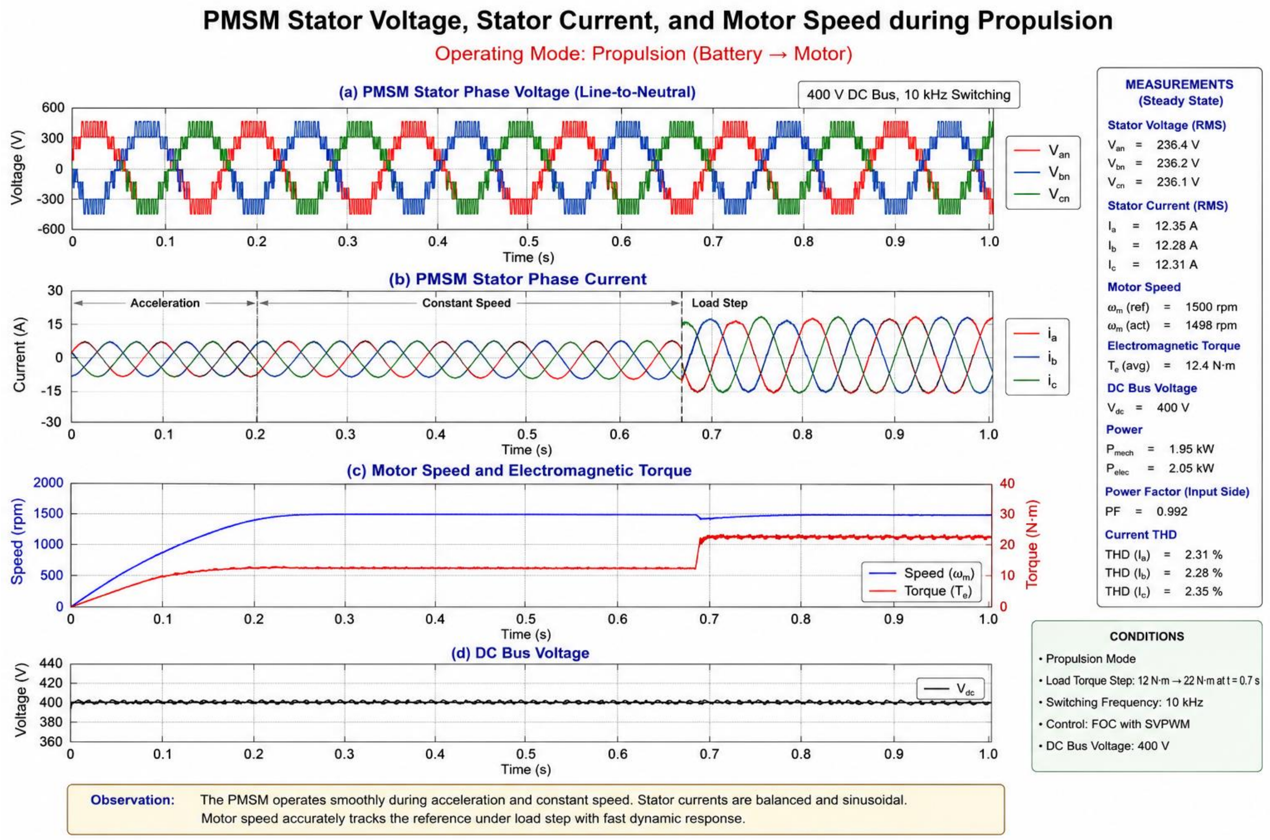

Fig. 6. PMSM Stator Voltage, Stator Current and Motor Speed during Propulsion

4) Regenerative Braking

During regenerative braking, the PMSM functions as a generator, converting mechanical energy into electrical energy. The generated power is transferred back to the battery through the bidirectional converter.
The simulation results confirm stable reverse power flow, controlled battery charging current, and smooth transition between propulsion and regenerative braking without excessive voltage overshoot.

D. Discussion

The simulation results demonstrate that the proposed Unified Multiport Matrix Converter can successfully perform multiple operating functions using a common power conversion platform. The elimination of the intermediate DC-link capacitor reduces converter complexity while maintaining efficient energy transfer in all operating modes.
The supervisory control algorithm enables seamless mode transitions, and the proposed digital control strategy ensures stable converter operation under varying load and operating conditions.
Overall, the simulation validates the feasibility of integrating AC charging, DC fast charging, propulsion, and regenerative braking into a single converter architecture suitable for next-generation electric vehicle applications.

VIII. RESULTS AND DISCUSSION

The proposed Unified Multiport Matrix Converter (UMMC) was evaluated under four operating conditions: AC charging, DC fast charging, propulsion, and regenerative braking. The MATLAB/Simulink results demonstrate that the proposed converter performs all operating modes using a common power conversion platform while maintaining stable operation and efficient power transfer.

A. AC Charging Performance

The three-phase input voltage and current waveforms obtained during AC charging are presented in **Fig. 5**. The simulation results show balanced sinusoidal input currents with negligible distortion throughout the charging process. The current waveforms remain almost in phase with the corresponding grid voltages, indicating near-unity input power factor operation.
The Direct Matrix Converter successfully converts the three-phase utility supply into a controlled high-frequency waveform without employing an intermediate DC-link capacitor. The elimination of the DC-link capacitor significantly reduces converter size while maintaining stable battery charging characteristics. The simulated Total Harmonic Distortion (THD) of the input current remains within acceptable limits, demonstrating the effectiveness of the proposed modulation strategy.

B. DC Fast Charging Performance

The Phase Shift Full Bridge converter accurately regulates the battery charging current through phase-shift control while maintaining galvanic isolation using the high-frequency transformer.
The charging current follows the reference value with minimal overshoot and fast settling time. The battery voltage increases smoothly according to the Constant Current–Constant Voltage (CC–CV)

charging profile. These results confirm the capability of the proposed converter to support efficient isolated charging with controlled current regulation.

C. Propulsion Performance

The propulsion characteristics of the PMSM are presented in **Fig. 6**. The stator voltages generated by the Direct Matrix Converter remain balanced throughout the operating period, while the stator currents exhibit smooth sinusoidal waveforms with low ripple. The Space Vector Pulse Width Modulation (SVPWM) algorithm provides precise control of the motor terminal voltage and current.
The motor speed closely follows the reference speed command with rapid dynamic response during acceleration. When a step change in load torque is introduced, the controller quickly restores the motor speed with negligible steady-state error. The electromagnetic torque exhibits stable operation with only a brief transient during load disturbance, demonstrating the effectiveness of the proposed Field-Oriented Control (FOC) strategy.

D. Regenerative Braking Performance

During vehicle deceleration, the PMSM operates as a synchronous generator and returns electrical energy to the battery through the bidirectional converter.
The battery charging current remains well regulated throughout the regeneration process, confirming stable reverse power flow. The supervisory controller automatically transitions between propulsion and regenerative braking without introducing significant voltage or current transients. This capability enables effective recovery of kinetic energy, thereby improving the overall energy efficiency of the electric vehicle.

E. Comparative Performance Analysis

A comparison between the proposed Unified Multiport Matrix Converter and a conventional EV power conversion system is presented in **Table II**.

TABLE II

COMPARISON OF THE PROPOSED CONVERTER WITH CONVENTIONAL EV POWER CONVERSION SYSTEMS

Performance Parameter	Conventional Architecture	Proposed UMMC
Number of Power Conversion Stages	4	2
Intermediate DC-Link Capacitor	Required	Eliminated
Bidirectional Power Flow	Partial	Full
AC Charging	Supported	Supported
DC Fast Charging	Supported	Supported
Propulsion	Separate Inverter	Integrated
Regenerative Braking	Separate Converter	Integrated
Galvanic Isolation	Yes	Yes

Performance Parameter	Conventional Architecture	Proposed UMMC
Component Count	High	Reduced
Estimated Power Density	Moderate	High
Digital Controller	Multiple Controllers	Single STM32 Controller

The comparison indicates that the proposed converter substantially reduces hardware complexity by integrating multiple operating functions into a common converter platform. The elimination of redundant conversion stages is expected to improve reliability, reduce installation space, and simplify thermal management.

F. Discussion

The simulation study confirms the feasibility of integrating charging, propulsion, and regenerative braking within a unified converter architecture. The proposed control strategy maintains stable operation under varying operating conditions while ensuring smooth transitions between operating modes.

The Direct Matrix Converter eliminates the need for an intermediate DC-link capacitor, thereby reducing passive component requirements and increasing expected system lifetime. The Phase Shift Full Bridge converter provides efficient isolated power transfer during charging, while the PMSM drive demonstrates excellent dynamic performance using Space Vector Pulse Width Modulation.

Although the present work is limited to simulation, the proposed architecture has been developed with practical hardware implementation in mind. The use of a commercially available STM32F407 microcontroller, standard power semiconductor devices, and conventional sensing techniques facilitates future prototype development. Experimental validation of the proposed converter will form the next phase of this research.

IX. CONCLUSION

This paper presented a **Unified Multiport Matrix Converter (UMMC)** for integrated electric vehicle charging, propulsion, and regenerative energy management. The proposed architecture combines a Direct Matrix Converter (DMC) with an isolated Phase Shift Full Bridge (PSFB) converter to perform multiple power conversion functions using a common hardware platform. By eliminating the conventional intermediate DC-link capacitor, the proposed converter reduces component count, improves power density, and enhances overall converter reliability.

The operating principles for AC charging, DC fast charging, propulsion, and regenerative braking were presented and analysed. A comprehensive mathematical model describing the Direct Matrix Converter, PSFB converter, high-frequency transformer, battery charging system, and PMSM drive was developed to establish the theoretical foundation of the proposed converter. Furthermore, a digital control strategy employing Space Vector Pulse Width Modulation (SVPWM), Sinusoidal Pulse Width Modulation (SPWM), and supervisory mode selection was proposed to ensure smooth transition between different operating modes while maintaining stable voltage regulation and bidirectional power flow.

The MATLAB/Simulink simulation results verified the feasibility of the proposed converter architecture. The simulation demonstrated balanced three-phase input currents during AC charging, stable battery charging characteristics during DC fast charging, accurate speed tracking during propulsion, and efficient energy recovery during regenerative braking. The proposed converter successfully integrated all four operating modes using a common converter structure without requiring additional power conversion stages.

Compared with conventional electric vehicle power conversion systems, the proposed Unified Multiport Matrix Converter offers several advantages, including reduced hardware complexity, elimination of the bulky DC-link capacitor, improved converter utilization, bidirectional energy transfer capability, galvanic isolation during charging, and simplified thermal management. These characteristics make the proposed converter a promising candidate for next-generation electric vehicle powertrain applications.

Although the present work has been validated through detailed simulation studies, experimental verification is required to further evaluate converter performance under practical operating conditions. Future work will focus on the development of a laboratory-scale hardware prototype using an **STM32F407-based digital controller**, implementation of real-time control algorithms, experimental validation under various charging and propulsion conditions, thermal performance analysis, efficiency optimization, and investigation of **Vehicle-to-Grid (V2G)** and **Vehicle-to-Home (V2H)** operating capabilities. The integration of advanced battery management techniques and artificial intelligence-based predictive energy management strategies will also be explored to further enhance the overall performance and reliability of the proposed converter architecture.

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