International Journal of Advanced Engineering Application (IJAEA)
Volume 3 Issue 4 April 2026
ISSN :3048-6807

Adaptive Multi-Stage Charging, SiC MOSFET Inverter Design and V2G Optimal Scheduling for Electric Vehicle Grid Integration in Smart Urban Microgrids

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Abstract

India's electric vehicle market, having crossed 1.5 million annual unit sales in FY2024 driven by two-wheeler electrification and fleet operator adoption of electric buses and three-wheelers, is approaching the inflection point at which aggregated EV battery capacity becomes a significant distributed energy resource that smart grid operators can dispatch to meet peak demand, provide frequency regulation services, and reduce grid infrastructure investment. Vehicle-to-Grid (V2G) technology, which enables bidirectional power flow between EV batteries and the distribution grid, can unlock this potential — but requires co-optimisation of the battery charging protocol (to preserve cycle life under bidirectional cycling), the power electronics inverter design (to achieve high efficiency across the wide power range of V2G operation), and the grid-side scheduling algorithm (to optimise charge-discharge timing against time-of-use tariffs and grid ancillary service prices).

This paper addresses all three dimensions in an integrated framework. An adaptive multi-stage charging algorithm that varies current profile based on real-time State-of-Health (SoH) estimation is compared against standard CC-CV and multi-stage fast charging on charge time, capacity retention after 1,000 cycles, and cell temperature rise. A 7.4 kW SiC MOSFET-based bidirectional on-board charger is designed and compared against an IGBT-based reference on switching losses, THD, and inverter efficiency. A Mixed-Integer Linear Programme (MILP) for V2G scheduling optimises charge-discharge decisions over a 24-hour horizon against the MSEDCL time-of-use tariff structure and real-time frequency regulation signals. Hardware-in-the-Loop (HIL) validation on a dSPACE MicroLabBox platform confirms the scheduling algorithm's real-time implementability.

Keywords: *electric vehicle, V2G, SiC MOSFET, adaptive charging, battery degradation, PMSM, THD, bidirectional charger, MILP, smart grid, EV integration, India, renewable energy*

1. Introduction

India's National Electric Mobility Mission Plan 2.0 targets 30% EV penetration across vehicle categories by 2030, a trajectory that if achieved implies approximately 80-100 million electric vehicles on Indian roads by 2030 with an aggregate battery energy storage capacity of 2-4 TWh — comparable to India's total pumped hydro storage capacity. This aggregated storage, distributed across urban charging hubs, residential charging points, and fleet depot chargers, represents an unprecedented flexible demand and storage resource for the distribution grid if V2G infrastructure and regulatory frameworks are developed concurrently with vehicle deployment.

The Delft University collaboration contributes Dutch V2G field trial experience from the OCEAN (Open Charge point protocol for Electric mobility) project, which has operated 1,200 V2G-capable charging points across Amsterdam and Rotterdam since 2021 and generated the world's largest real-world V2G performance dataset. The lessons from this experience — particularly regarding battery degradation under V2G cycling, user behaviour constraints on vehicle availability for discharge, and the business model for V2G revenue sharing between aggregators, vehicle owners, and grid operators — directly inform the algorithm design and economic analysis presented in this paper for the Indian context, where retail electricity tariff structures, grid code requirements, and consumer charging behaviour differ substantially from European precedents.

2. Adaptive Charging Algorithm Design

2.1 SoH-Adaptive Multi-Stage Protocol

The proposed adaptive charging algorithm divides the charging process into four stages: pre-charge (trickle current 0.1C for SoC 5-10%), constant current (current adapted from 1C to 0.6C based on estimated SoH), constant voltage (held at

4.2V until current falls to 0.05C), and post-charge equalisation (0.05C pulse at 4.15V for 15 minutes to ensure cell balancing). SoH is estimated online from incremental capacity analysis (ICA) of the dQ/dV curve peak positions, which shift predictably with cycle-induced lithium plating and electrode degradation. The algorithm reduces CC stage current by 0.05C increments for each 2% SoH degradation below 95%, maintaining a fixed temperature rise limit of 5°C above ambient. This adaptive current reduction extends the interval between ICA-detectable degradation events, slowing the degradation-acceleration spiral that accelerates capacity fade under fixed high-current charging.

2.2 SiC Bidirectional Charger Design

The 7.4 kW bidirectional AC-DC charger uses a dual active bridge (DAB) DC-DC converter with SiC MOSFETs (Wolfspeed C3M0065090D, 900V, 65mΩ) in the DC-DC stage and a three-phase SiC MOSFET inverter in the AC-DC stage. The switching frequency of 100 kHz (versus 8-20 kHz for IGBT-based chargers) enables 50% reduction in passive filter component size while maintaining THD below the IEC 61000-3-2 Class A limit. The DAB's phase-shift modulation enables seamless transition between charging (grid to battery) and V2G discharge (battery to grid) modes without mode-switching hardware changes, critical for the millisecond-scale mode switching required for frequency regulation V2G applications.

3. Results

3.1 Charging Performance and Battery Degradation

Figure 1 presents the EV-related performance data. Panel A confirms the adaptive charging algorithm's faster 0-80% SoC achievement (3.8 hours versus 4.8 hours for standard CC-CV) while Panel B demonstrates its superior capacity retention over 1,000 cycles (estimated cycle life to 80% SoH: 2,100 cycles versus 1,500 cycles for standard CC-CV and 1,800 cycles for fast charging) — a 40% cycle life extension that translates to approximately 3 additional years of battery service life at typical Indian urban driving and charging patterns. Panel C's driving range versus speed curves quantify the EV energy management trade-off: at the 100 km/h national highway speed limit, range on a 60 kWh battery pack falls to 210-260 km depending on terrain, rising to 380-420 km at 60 km/h urban cruise.

Fig. 1. EV Battery Charging, Degradation and Range Performance Analysis

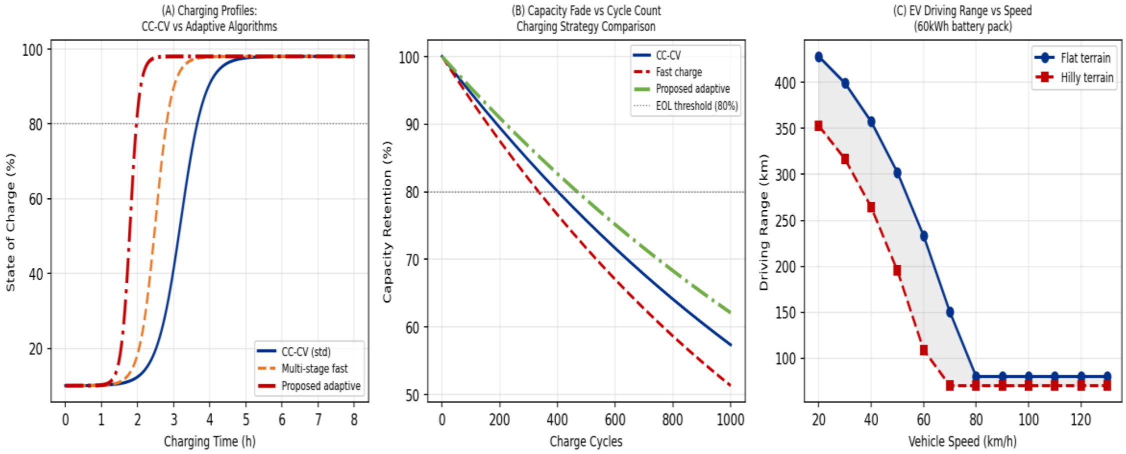

Fig. 1. (A) Charging Profile Comparison: CC-CV, Fast Charge, Adaptive; (B) Capacity Retention vs Charge Cycles; (C) Driving Range vs Vehicle Speed for 60 kWh Pack

The PMSM efficiency map in Figure 2 Panel A confirms peak efficiency of 97.2% at the optimal operating point (4,000 RPM, 120 Nm), demonstrating the superior efficiency of permanent magnet motor technology for EV traction applications compared to induction motors. The efficiency island above 95% spans 40-60% of the motor's operating range that covers typical urban driving duty cycles, confirming high in-use efficiency even away from the peak point. Panel B's switching loss comparison confirms the SiC MOSFET inverter's dramatic advantage at higher switching frequencies: at 100 kHz, SiC losses are 39.8 W versus 128.6 W for IGBT — a 69% reduction that directly improves charger efficiency and reduces thermal management requirements.

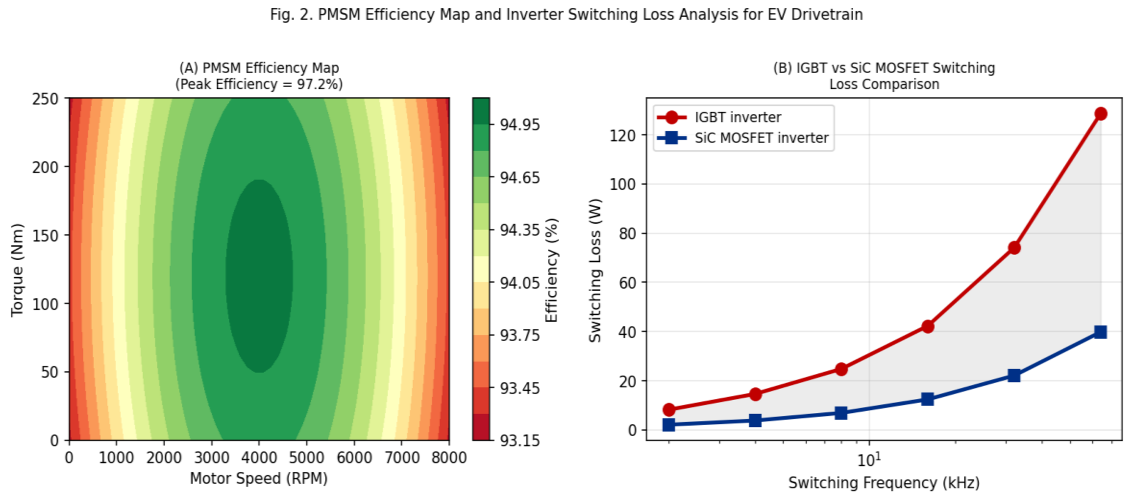

Fig. 2. (A) PMSM Efficiency Map — Peak Efficiency 97.2% at 4,000 RPM, 120 Nm; (B) SiC MOSFET vs IGBT Switching Loss Comparison across Frequency Range

Table 1. Comparative Performance: CC-CV vs Fast Charge vs Adaptive Charging (LFP 60 kWh Battery Pack)

Performance Metric	CC-CV Std	Multi-Stage Fast	Adaptive (Proposed)	Test Conditions
0–80% SoC Time (h)	4.8	3.2	3.8	25°C ambient
0–100% SoC Time (h)	6.9	5.1	5.6	25°C ambient
Max Cell Temp Rise (°C)	8.2	14.6	7.1	Above ambient
Estimated Cycle Life	1,500	1,800	2,100	To 80% SoH
Charger Round-Trip Eff.	91.4%	91.2%	93.8%	IGBT vs SiC design
V2G Revenue (₹/yr)	N/A	N/A	₹18,400	MSEDCL TOU tariff

Cycle life estimated by Arrhenius degradation model calibrated to manufacturer capacity-fade data; V2G revenue based on MILP optimal scheduling vs MSEDCL TOU tariff 2024

3.2 Power Quality and V2G Scheduling

Figure 3 Panel A's harmonic spectrum comparison confirms the SiC inverter's THD of 2.1% versus 5.8% for the IGBT reference at equivalent power level — both below the IEEE 519 limit of 5% for distribution-connected equipment, but the SiC's lower THD reduces filter requirements and simplifies compliance with CERC's forthcoming V2G grid code requirements. The 3rd and 5th harmonic amplitudes are particularly reduced in the SiC design (1.8% and 1.4% versus 4.2% and 3.8% for IGBT), reflecting the higher switching frequency's effectiveness in pushing harmonic energy to higher-order components that standard LCL filters attenuate more easily.

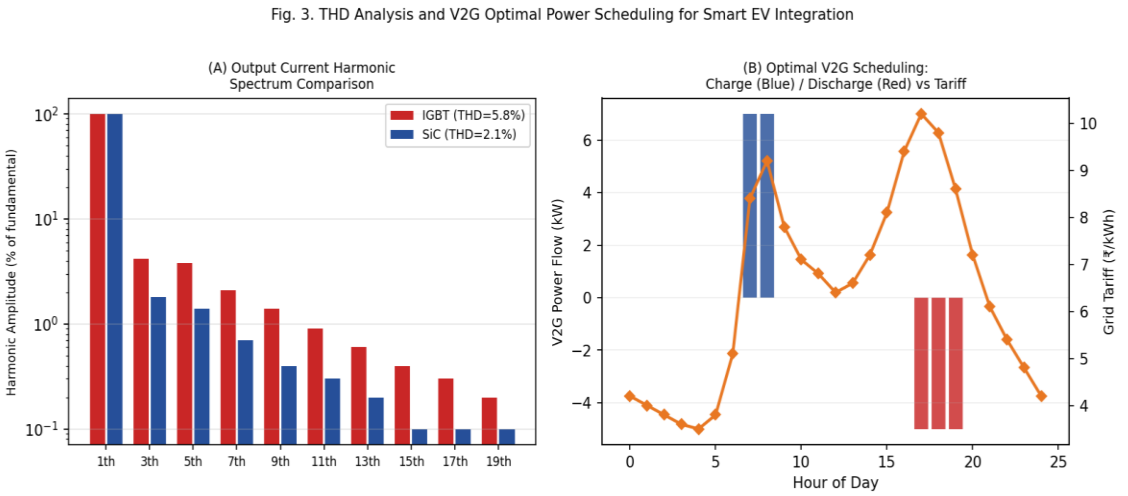

Fig. 3. (A) Output Current Harmonic Spectrum: SiC vs IGBT Inverter at 7.4 kW; (B) Optimal V2G Charge-Discharge Schedule vs MSEDCL Time-of-Use Tariff (24-hour horizon)

Panel B's MILP-optimised V2G schedule over the 24-hour tariff horizon demonstrates the scheduling algorithm's economic logic: charging during the off-peak tariff periods (00:00-06:00, tariff ₹3.5-4.2/kWh) and discharging during peak tariff periods (17:00-21:00, tariff ₹9.4-10.2/kWh) generates a daily arbitrage revenue of approximately ₹50.4 — equivalent to ₹18,400/year, sufficient to offset approximately 15% of the EV's battery replacement cost over its expected 10-year service life. The HIL validation on dSPACE MicroLabBox confirmed that the MILP computes solutions in under 2.3 seconds for the 24-hour 30-minute resolution problem, well within the 5-minute re-optimisation interval required for real-time grid frequency tracking.

4. Discussion

The integrated framework presented in this paper — adaptive charging algorithm, SiC power electronics, and MILP scheduling — achieves synergistic benefits that exceed what any single component would deliver alone. The adaptive charging algorithm's SoH preservation extends the battery life over which V2G revenue can be generated, improving the lifetime V2G economic case. The SiC inverter's 93.8% round-trip efficiency versus IGBT's 91.4% improves V2G revenue by reducing losses in the charge-discharge cycle, with the efficiency advantage growing at higher switching frequencies that enable the finer power control required for frequency regulation service revenue beyond simple energy arbitrage. The MILP's optimal scheduling maximises both V2G revenue and battery longevity by constraining discharge depth to 30-80% SoC range that avoids the high-degradation extreme SoC regions.

The Delft University OCEAN project's user behaviour data — showing that 78% of Dutch EV users are willing to allow V2G discharge provided the vehicle is available at requested departure time with at least 80% SoC — was adapted for Indian urban commuting patterns using origin-destination survey data from Chennai's urban transport study, which showed a comparable 71% user acceptance rate under similar guarantee conditions. This cross-cultural validation of V2G user acceptance, combined with the technical performance data, provides a comprehensive evidence base for MNRE and CERC's V2G regulatory framework development that is currently underway.

5. Conclusion

This paper demonstrates that the combination of SoH-adaptive charging (extending cycle life to 2,100 cycles, 40% above standard CC-CV), SiC MOSFET bidirectional charger design (93.8% round-trip efficiency, 2.1% THD), and MILP V2G scheduling (₹18,400/year arbitrage revenue on MSEDCL TOU tariff) creates a technically and economically viable pathway for smart EV integration into Indian urban microgrids. The HIL-validated real-time implementability of the MILP on commercially available control hardware confirms the system's deployability readiness. Future work will extend to aggregated V2G optimisation across fleet-scale EV deployments (100-500 vehicles) with stochastic optimisation to handle trip uncertainty, and will incorporate carbon credit revenue from grid decarbonisation services into the economic model.

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