



# MULTI-OBJECTIVE OPTIMIZATION-DRIVEN ADAPTIVE CONTROL FRAMEWORK FOR BIDIRECTIONAL EV CHARGING COMBINED WITH HYBRID ENERGY SYSTEMS.

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**Abstract**—This paper presents the integrated charging chart-objective optimization-operated adaptive control framework with hybrid energy systems for integrated charging with hybrid energy systems. The purpose of the framework is to simultaneously reduce energy loss, reduce operating costs, maintain voltage stability and increase load management in the distribution grid with high EV entry and renewable energy sources. Taking advantage of advanced metaheuristic optimization algorithms, the position of the framework grid prepares the EV behavior and renewable generations for different time, ensuring efficient and reliable grid operations. Simulation results display significant improvements in cost reduction; energy efficiency and grid stability compared to traditional methods.

**Keywords**—Bidirectional EV Charging (V2G, V2H, V2L), Hybrid Energy Systems (HES).

## I. INTRODUCTION

The rapid growth of electric vehicles (EVs) and the increased penetration of renewable energy sources (RES) are resulting in the transformation of contemporary power systems into decentralized systems focused on sustainability. EVs, being a consumer of energy, are transforming into flexible energy storage devices in that they have the capacity to provide power interchange bidirectionally with vehicle-to-grid (V2G), vehicle-to-home (V2H), and vehicle-to-load (V2L). As a component of hybrid energy systems (HES), which include solar, wind, and energy storage, provide flexibility to increase energy usage resilience,

peak load shaving, and maximum RES accessibility. Some challenges exist in this integration such as renewable generation variability, uncertainty with respect to EV users, and balancing battery health while maintaining grid reliability and stability.

To resolve these difficulties, this research develops a multi-objective optimization-based adaptive control scheme. Different from the traditional single-objective approach, this new approach attempts to achieve several objectives at once based on the hierarchical objective levels (in this case, minimizing the energy cost, reducing the battery degradation, respecting the user charging preferences, and positively contributing to the grid services). The system architecture involves the renewable energy generation, hybrid energy storage system (HES), and bidirectional EV chargers, which are coordinated by a central energy management system (EMS) while implementing real-time forecasting, optimization, and feedback control in determining the power flow in the system in a dynamic and efficient manner.

The framework also includes adaptive control methods — including Model Predictive Control (MPC) and reinforcement learning — to consider possible shifting behaviors from variations in load demand, weather, and signals from the grid. Based on simulations from actual profiles, the proposed system can markedly enhance economic performance, user-satisfaction and operational efficiency. The results lend support for the deployment of intelligent EV-integrated hybrid system in a future smart grid and inherent scalability in their use.

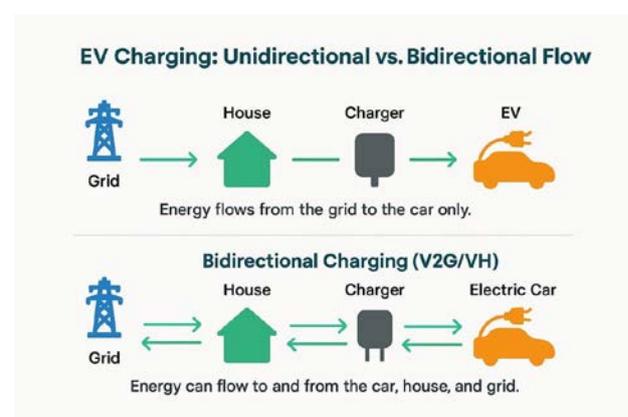
This research proposes a novel multi-objective optimization-driven adaptive control

framework for bidirectional EV charging integrated with hybrid energy systems. The framework not only optimizes power flows in real time but also adapts dynamically to system variations while ensuring the safe and efficient operation of the entire energy infrastructure. By leveraging forecasted data, user preferences, and real-time measurements, the proposed system ensures optimal energy dispatch and enhances the interaction between EVs, distributed energy resources (DERs), and the smart grid. Simulation studies validate the system's performance, demonstrating significant improvements in energy cost savings, battery health management, grid reliability, and user satisfaction.

## II. LITERATURE SURVEY

Many studies have looked at the integration of electric vehicles (EVs) with the grid using bidirectional charging techniques, such as Vehicle-to-Grid (V2G), Vehicle-to-Home (V2H), and Vehicle-to-Load (V2L). The V2G concept originated from Kempton and Tomic, showing that EVs could provide power to the grid when needed during peak demand periods to improve grid stability. A number of studies showed that EV smart charging could double the benefits of intermittent renewable energy resources when following dynamic pricing signals. There are still many challenges including unpredictable user behavior, battery degradation, and renewable energy resource variability which can benefit from a more intelligent control process. Hybrid energy systems (HES) combining a grid connection with energy sources such as solar and wind, and with hybrid energy storage systems (HESS), have been demonstrated to support increased overall system flexibility and self-sufficiency in energy. Many developed studies have enhanced energy dispatch using methods from Model Predictive Control (MPC) and heuristic-based scheduling, but often do not take into account both adaptability to real-time changing conditions (such as uncertain user behaviour) and the maximum obtainable scheduling considering user constraints simultaneously. There have been recent approaches in multi-objective optimization and reinforcement learning that have begun to bridge this gap.

Even so, there has yet to be a rigorous, real-time, or in the case of energy and finance, synchronously, comprehensive framework to collaboratively coordinate EV charging operations with HES energy management in real-time for optimizing multiple conflicting objectives. This remains an open area of research which forms the basis of this work.



## III. SYSTEM ARCHITECTURE

The proposed system architecture for the integration of bidirectional electric vehicle (EV) charging and hybrid energy systems (HES) aims to create a smart, adaptive energy management framework. The proposed system is centred on a centralized Energy Management System (EMS) that decides and orchestrates power exchanges between distributed renewable energy sources (solar photovoltaics or wind turbines), hybrid energy storage systems (HESS), bidirectional EV chargers, and the utility grid. The proposed system is based on a direct current (DC) microgrid that eliminates power conversion losses in systems requiring alternating current (AC) to DC conversion and enables high-efficiency operation. As renewable sources can connect to the DC bus through power electronic interfaces, upon the introduction of renewable sources, the controlling EMS will dynamically and instantaneously control power output. The EMS includes forecasting models for solar irradiance, wind availability, load demand, and electricity pricing, thus enabling the system to indicate or make optimal decisions around charging and discharging schedules. Smart meters, sensors, or other components can be utilized to provide real-time feedback about voltage, current, state of charge (SOC), and grid status.

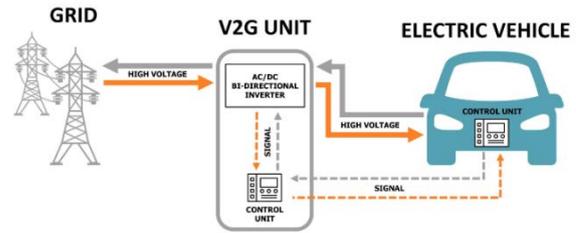


Bidirectional EV chargers conforming to ISO 15118 and IEC 61851 standards enable G2V, V2G, and V2L operations. User inputs such as SOC to be maintained and time of departure are integrated into an optimization model to solve for the EMS. The hybrid energy storage system comprises batteries for the long-term energy supply and supercapacitors to cater short-term power fluctuations. The HESS is controlled by high-efficiency bidirectional converters to balance power demands while reducing battery discoloration. A multi-objective optimization based on ANTS algorithm is run by the EMS to minimize energy cost, protect battery life, adhere to user constraints, and provide grid reliability. Adaptive control methods, including Model Predictive Control (MPC) or reinforcement learning, are used continuously to adapt the operational commands to shifts in operating conditions and ensure efficient, stable, and user-friendly real-time conditions.

#### A. Vehicle-to-Grid (V2G)

Vehicle-to-Grid (V2G) technology not only allows electric vehicles (EVs) to draw power from the grid when they are charging, but also can deliver back excess stored energy into the grid at the utility's request. When EVs provide the V2G services, it is bidirectional and can provide the additional means of multi-purposing battery capabilities for grid services in frequency response, peak load shaving, and voltage stabilisation. V2G technologies hinge on intelligent bidirectional charging and communication interfaces that facilitate and communicate the EV's discharging schedule with the grid requirements. When smart technology is used for coordination and deployment of EVs, demand response can convert parked EVs into distributed energy storage. This capability establishes demand-side energy management and grid decarbonisation and increases the flexibility and reliability of renewable-based smart grids.

#### V2G (Vehicle to Grid)



#### B. Vehicle-to-Home (V2H)

Vehicle-to-Home (V2H) enables an electric vehicle (EV) to serve as a primary or secondary energy source for a home. In this case, the EV could supply electricity to a home in the event of a power outage or during peak tariff periods to assure the home receives energy when needed and at a lower price. In practice, this will require some type of an integrated energy management system, an inverter, and occasionally an automatic transfer switch to separate the home from the grid while the V2H is being used. The use of an EV as a home storage option in support of EV2H, also enhances energy resilience at the neighbourhood level through decentralization and self-sufficiency by homes with solar PV and other renewable energy resources.

#### C. Vehicle-to-Load (V2L)

Vehicle-to-Load (V2L) is the most basic form of bidirectional EV power use, where the vehicle draws on electricity to power external devices and appliances. V2L is often used in off-grid situations including camping, working remotely, or in emergency situations, providing power via built-in AC outlets and/or on-board inverters. Compared to V2G or V2H, V2L does not require complex integration with the grid or home energy systems. Rather, V2L uses the mobility and energy storage potential of EVs to provide power wherever it is needed in a convenient, portable way that is well-suited for short-term, or in some instances one-time, needs.

## IV. MULTI-OBJECTIVE OPTIMIZATION FORMULATION

The identified energy management system engages in a portfolio of multi-objective optimization methods to solve a number of conflicting objectives at the same time, where the goal is to minimize electricity cost, maximize renewable energy usage, minimize battery degradation, and charge an electrical

vehicle (EV) under the user's specified time constraint. The problems are posed as a single cost function by weighing each objective and applying penalty terms to the cost function to reflect importance. The optimization problems are not solved without operational constraints including balancing power (supplies = demands), state-of-charge (SOC) limits, converter limits, grid export limits, and grid import limits. To aid the decision making process, predictive signals of solar irradiation, load demand, and time-of-use rates are integrated to the model. Mixed-Integer Linear Programming (MILP) or Pareto-based evolutionary algorithms are used to arrive at schedules for dispatching the bidirectional EV chargers, the hybrid energy storage systems, and the renewable sources. The solution is then transmitted to the adaptive control layer for real-time action, continuing to meet the specified objectives under conditions of change and uncertainty.

## **V. ADAPTIVE CONTROL STRATEGY**

The adaptive control scheme is meant to be flexible to changing conditions related to system requirements such as changing renewable energy generations, user-specific EV charging preferences, and changing demands of the grid. An important aspect is the fact that this approach relies on ongoing feedback by continuously measuring the state of the core attributes of the system which includes: state of charge (SOC), power flow, voltage levels, and load demand. By providing forecasting information (e.g., weather and load prediction), the Energy Management System (EMS) can detect conditions that will require updating the control signal in order to optimize performance. Control actions will typically make use of techniques such as Model Predictive Control (MPC), the aim is to predict future states of the system and select control actions that minimize a cost function over a moving horizon while respecting the constraints of the system.

## **VI. CONVERTER TOPOLOGIES AND CONTROL MECHANISMS**

Bidirectional AC-DC converters provide a key interface for energy flow between the power grid and electric vehicles (EV). The topologies of these converters usually employ pulse width modulation (PWM) rectifier or multilevel inverter type converters. They

operate during charging and discharging modes. In charging mode they take AC power supply from the grid and convert it into DC power to charge EV batteries. During Vehicle-to-Grid (V2G) operation, they take EV batteries energy storage and return it to the grid as synchronized AC through the phase-locked-loop (PLL). These converters can also support reactive power control and mitigate power quality issues by correcting the power factor and compress the harmonic distortions.

Bidirectional DC-DC converters store the power from the EV batteries to high-voltage DC energy storage systems, like super capacitors, and renewables sources as DC sources, like the photovoltaic (PV) panel. The Buck-boost converter topologies provide the electrical interface to step up or step down the voltage as mandated during the operational environment. Because of the significant impact of ripple current, interleaved configurations are employed, which will also improve thermal performance. For specific applications in the hybrid energy system requiring voltage regulation, reduced noise or specific gain, more sophisticated topologies, such as the SEPIC (Single-Ended Primary-Inductor Converter), Cuk, and Luo converters are used.

Isolated DC-DC converters are applicable, when electrical isolation is a design requirement for either safety or regulation. Typical use cases include fast charging applications and in high voltage system designs. Isolated converters can be full bridge, half bridge, or push-pull, all of which use a high frequency transformer to electrically isolate the primary and secondary sides of the converter while allowing efficient power transfer. In addition to having the ability to provide many times greater voltage gain than a non-isolated converter, isolated converters are also electrically isolating and, therefore usable for connecting to renewable energy sources and effectively connecting electrically with EV batteries.

Multiport converters typically reduce the size of the combined unit compared to multiple separate converters for the separated power sources/storage connections. Instead of using multiple converters to convert power from various inputs (e.g., PV panels, grid, batteries, EVs, etc.) and/or outputs through different associated conversion losses, all inputs, and outputs can be used within a single unit to overcome projected conversion losses and lower

associated hardware costs. In terms of converter topologies examples, layers of management include Triple Active Bridge (TAB) converters and Multi-Port converters (MISO) converters. Multiport converters also enhance operational flexibility and lower the complexity of control in energy distributed systems and associated hardware.

Lastly, DC-AC inverters are seen both on the EV (traction system) and off-board (grid interaction). Inverters convert stored DC energy to AC either to drive the EV AC motors or inject energy back into the grid during V2G operations. Voltage Source Inverter (VSI) topologies are often used, supporting single-phase or three-phase output, harmonic filtering, and synchronization to grid frequency and voltage. The fast-switching characteristics and modulation techniques afford a high level of efficiency and control over output waveform quality.

Control mechanisms are important to ensure the efficient, coordinated, and stable operation of bidirectional EV charging with hybrid energy systems. In this respect, at the centre of the mechanism is an Energy Management System (EMS) which functions as a decision-making entity to balance energy flow between EVs, renewable energy sources, energy storage systems, and the energy grid. The EMS consists of monitoring in real-time, forecasting algorithms, and load prediction models to predict energy generation (for example, solar, wind), EV user demand and grid supply/demand conditions. Subsequently, in real time, the EMS dynamically generates control signals for converters and switching devices to address the main goals of system performance with minimal user cost, dedicated peak shaving and battery life extension. Control solutions could be realised using model predictive control (MPC) or Fuzzy Logic Controllers.

## VII. CONCLUSION

This research showcases a novel adaptive control framework for bidirectional electric vehicle (EV) charging with hybrid energy systems through a multi-objective optimization approach for resilient grid energy management, improved energy efficiency, and better end-user experiences. The proposed multi-objective adaptation framework includes a range of intelligent converter topologies, real-time adaptive control techniques, and predictive multi-

objective optimization tools to meet conflicting objectives such as reducing costs, maximizing renewable energy consumption, and maintaining battery health. The development of advanced control techniques and flexible power converters will allow bidirectional energy flow to seamlessly occur between the EVs with renewable sources and the grid. The framework represents a promising advancement in supporting future smart grid development, demand-side management and sustainable mobility delivery as part of a worldwide effort towards clean and reliable energy infrastructures.

## REFERENCES

1. P. He and A. Khaligh, "Comprehensive Analyses and Comparison of 1 kW Isolated DC-DC Converters for Bidirectional EV Charging Systems," in *IEEE Transactions on Transportation Electrification*, vol. 3, no. 1, pp. 147-156, March 2017, doi: 10.1109/TTE.2016.2630927.
2. T. He, M. Wu, D. D. -C. Lu, R. P. Aguilera, J. Zhang and J. Zhu, "Designed Dynamic Reference With Model Predictive Control for Bidirectional EV Chargers," in *IEEE Access*, vol. 7, pp. 129362-129375, 2019, doi: 10.1109/ACCESS.2019.2940214.
3. B. Mroczek and A. Kołodyńska, "The V2G Process With the Predictive Model," in *IEEE Access*, vol. 8, pp. 86947-86956, 2020, doi: 10.1109/ACCESS.2020.2991329.
4. H. Shin and R. Baldick, "Plug-In Electric Vehicle to Home (V2H) Operation Under a Grid Outage," in *IEEE Transactions on Smart Grid*, vol. 8, no. 4, pp. 2032-2041, July 2017, doi: 10.1109/TSG.2016.2603502.
5. J. Yuan, L. Dorn-Gomba, A. D. Callegaro, J. Reimers and A. Emadi, "A Review of Bidirectional On-Board Chargers for Electric Vehicles," in *IEEE Access*, vol. 9, pp. 51501-51518, 2021, doi: 10.1109/ACCESS.2021.3069448.
6. K. Kim and W. Park, "Study on the Safety and Mechanical Test Method of Vehicle to Load(V2L) Adapter," 2024 4th International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME), Male, Maldives, 2024, pp. 1-5, doi: 10.1109/ICECCME62383.2024.10796122.

7. Y. Li, Z. Shuai, X. Liu, Y. Hong, X. Wu and Z. J. Shen, "Stability Investigation of Bidirectional AC-DC Converter Considering Operating Conditions," in IEEE Access, vol. 8, pp. 131499-131510, 2020, doi: 10.1109/ACCESS.2020.3009360.
8. S. A. Gorji, H. G. Sahebi, M. Ektesabi and A. B. Rad, "Topologies and Control Schemes of Bidirectional DC-DC Power Converters: An Overview," in IEEE Access, vol. 7, pp. 117997-118019, 2019, doi: 10.1109/ACCESS.2019.2937239.
9. C. -H. Hsieh, T. -J. Liang, S. -M. Chen and S. -W. Tsai, "Design and Implementation of a Novel Multilevel DC-AC Inverter," in IEEE Transactions on Industry Applications, vol. 52, no. 3, pp. 2436-2443, May-June 2016, doi: 10.1109/TIA.2016.2527622.