IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 12, April 2025
Impact Factor: 7.67

Control and Optimization Strategies for DC Microgrid-Based EV Charging Infrastructure

M. Ahire Aditi Kewal[1], Dr. Tapre P. C.[2], Dr. Fareed Ahmad[3]
S.N.D. College of Engineering and Research Center ,Yeola.
ahireaditi9@gmail.com, hodelectrical@sndcoe.ac.in, fareed.ahmad@sndcoe.ac.in

Abstract: *The widespread adoption of electric vehicles (EVs) introduces new challenges for conventional power distribution systems, particularly during periods of high demand. In response, this study proposes an intelligent control strategy for EV charging infrastructure based on a DC microgrid. The system integrates photovoltaic (PV) generation, battery storage, and grid support to ensure reliable, efficient energy delivery while minimizing grid dependency. A rule-based decision mechanism is developed to manage charging modes—fast, average, and slow—based on real-time power availability and user preferences.*

The proposed model simulates power flow across multiple sources, dynamically adjusting charging priorities to maintain voltage stability and optimize energy use. A microcontroller-based platform is used to validate the control logic through hardware and simulation, demonstrating improved energy autonomy and system responsiveness. Results confirm that the approach enhances power quality, supports flexible charging behaviour, and contributes to the development of sustainable EV infrastructure supported by renewable energy sources..

Keywords: Electric Vehicle, DC Microgrid, Power Management Strategy, Energy Storage System

I. INTRODUCTION

EVs are at the forefront of clean energy activities as a result of the global shift toward sustainable transportation. However, conventional power distribution systems are under a lot of strain due to the increased demand for EV charging, especially during hours of peak usage. In order to enable EV charging infrastructures, DC microgrids have become a viable architectural concept for combining energy storage systems with renewable energy sources like photovoltaics. In addition to enabling localized energy production and consumption, these microgrids have enhanced control capabilities, which are essential for handling sporadic generation and a range of charging needs.

In a DC microgrid, optimizing EV charging station performance requires sophisticated control systems that can adapt to changing user behavior and energy supply. This involves prioritizing energy allocation, intelligent load shedding, and real-time power distribution while adhering to user expectations and physical system limitations. The suggested system seeks to improve energy autonomy and reduce grid dependency by utilizing models for forecasting and decision-making algorithms. This study offers a thorough control and optimization approach that has been verified by in-depth simulations, emphasizing its capacity to preserve system stability while enhancing user satisfaction and energy efficiency.

II. LITERATURE REVIEW

For DC microgrids powering EV charging stations to operate steadily and optimize power flow, efficient energy management systems (EMS) and control strategies are essential. An EMS of a DC microgrid that integrates solar PV arrays and wind plant to supply EV charging stations was proposed by Sayed et al. [1]. Their method, which has been verified by MATLAB/Simulink simulations, maximizes the capabilities of battery storage and renewable energy sources (RES) to lessen the unpredictability of solar and wind power supply. Similar to this, Wang et al. [2] offered a distributed virtual-battery-based droop control approach that regulates the state of charge (SOC) of energy storage system, improves PV usage, and preserves bus voltage stability. As seen in actual EV charging situations, their approach increases voltage tracking and lessens grid dependency when compared to traditional droop management.

The use of sliding mode control (SMC) and fuzzy logical control (FLC) for a DC microgrid with EV fast-charging points were investigated by Mohammed et al. [3]. With SMC exceeding FLC in dynamic performance, their method uses EV batteries as a distribution static compensator (D-STATCOM) to reduce voltage sags. For energy management, Mohan and Dash [4] suggested a hybrid fuzzy-sparrow search algorithm (SSA), which outperformed particle swarm optimization (PSO) in terms of stability and convergence. By managing power balance under changing solar radiation and battery SOC, their technology provides cost-effective operation and saves roughly 7.776% on annual electricity expenses.

Abraham et al. [5] investigated fuzzy logic-based control further and created an independent EMS for a PV-powered EV charging station. According to simulation and practical data, its bidirectional converter control guarantees a steady power distribution under fluctuating PV output and SOC levels. In their assessment of different microgrid topologies and control schemes, Savio Abraham et al. [6] emphasized the function of EMS in optimizing RES use and reducing grid dependency. Power flow between PV, ESS, and electric vehicle charging terminals is efficiently managed by their experimental EMS.

In order to increase the efficacy of DC microgrid-based EV charging systems, sophisticated control approaches have been put out. A fractional-order proportional integral (FOPI) controller tuned using the grey wolf optimization (GWO) technique was presented by Zaid et al. [7]. Their method outperforms conventional PI controllers in terms of resilience and transient response under changing solar insolation. A multi-level integrated management architecture for an islanded direct current microgrid with fault ride-through (FRT) capabilities was presented by Faraji et al. [8]. In order to ensure dependable operation under a variety of circumstances, including AC breakdowns, their central control system regulates generation, consumption, and storage.

Savio et al. [9] developed a fuzzy-controlled bidirectional converter for a two-plug EV charging station, maintaining power distribution in a decentralized manner. Their system was validated through simulations and a laboratory-scale prototype. Similarly, Savio et al. [10] proposed a hybrid microgrid-powered charging station with a charge controller for constant current and voltage charging, reducing charging time and enhancing RES utilization through a closed-loop EMS.

Optimal sizing and placement of microgrid components are crucial for cost-effectiveness and performance. Aluisio et al. [11] offered a procedure for techno-economic sizing of a direct current microgrid for EV fleet charging, incorporating modular device structures and EV commitment strategies. Their approach was applied to a case study for the Bari port authority, demonstrating practical applicability. Krishnamurthy et al. [12] used a improved teaching-learning-based optimization (TLBO) technique to enhance the placement and sizing of EV charging stations and RES in a direct current microgrid. Their method minimizes voltage stability issues, power losses, and costs, achieving significant improvements in voltage profiles and the voltage-reliability-power loss (VRP) index.

In their comparison of both alternating current and direct current microgrids for EV charging, Cleenwerck et al. [13] emphasized the aids of a low-voltage DC (LVDC) support in terms of lowering power losses and enhancing voltage stability. With greater EV and PV penetration, their power flow study demonstrated improved energy efficiency. For a standalone DC microgrid, Pan et al. [14] suggested an energy coordination control technique that included enhanced droop control created on battery state of charge (SOC) and tracking of maximum power point. Their method lowers ESS capacity redundancy while improving system stability.

A combination of the Kepler optimized algorithm–dilated residual network (KOA–DRN) technique was presented by Sowrirajan et al. [15] in order to reduce the loss of energy and charge time in EV charging stations. With a time to settle of 0.02 seconds and a loss rate of 1.2%, their approach performs better than other optimization approaches like PSO, indicating more efficiency.

III. METHODOLOGY

The modular design of a DC microgrid-based EV charging station is at the center of the methodological framework created for this investigation. Three primary power sources make up the system: a bidirectional public grid link, an electrochemical battery backup unit, and photovoltaic (PV) panels. According to the user-selected charging modes—fast, average, and slow—the charging infrastructure is modeled to comprise a number of EV chargers with different power requirements. To simulate system dynamics and operating conditions in real time, every component is mathematically modeled and incorporated into an overall simulation platform.

To reduce energy costs and increase system efficiency, this engine takes user preferences, power availability, and stochastic arrival times into account. Based on charge occupancy duration and charge urgency, an order of priority is used to control load shifting and restoration activities. A DC microgrid-integrated EV charging station is depicted in the block diagram, which shows how many EV chargers, energy storage, renewable energy sources, and the public grid interact in concert. A DC bus, which acts as the main energy distribution conduit and facilitates efficient and seamless power flow among all components, is at the center of the system.

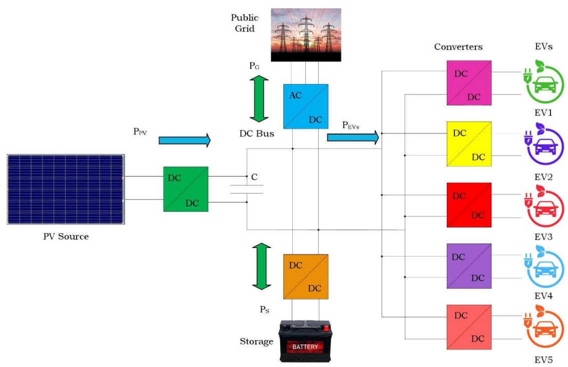


Fig. 1 DC Microgrid with EV Station

The EV station based on DC microgrid shown in Fig. 1. The main source of renewable energy is the photovoltaic, or PV, source, which is located on the left. A DC-DC converter, which controls voltage and guarantees compatibility with the microgrid, connects it to the DC bus. When solar conditions are favorable, the PV panels' output power, or PPV, is given priority for charging. A system for storing energy from batteries is incorporated beneath the PV system using a separate DC-DC converter. With power exchange designated as PS, this unit supplies electricity when photovoltaic power is low or demand increases and absorbs excess energy throughout peak solar generation.

A reversible AC-DC converter connects the system to the public power grid. This link improves grid involvement and flexibility by enabling the charging facility to export surplus energy when available or import energy when its own resources are insufficient. The power exchanged here is indicated as PG. To stabilize voltage across the DC bus and provide support during rapid load changes, a capacitor bank (C) is placed in parallel with the bus.

On the right side, five EV charging points (EV1 to EV5) are shown, each equipped with an individual DC-DC converter. These converters adapt the bus voltage to suit the requirements of each EV and support various charging modes—fast, average, or slow—based on user preferences and power availability. The total power delivered to all EVs is labelled PEVs. The flow of power through the system is designed with a priority order: PV power is utilized first, followed by battery storage, and lastly, the public grid as a backup. This arrangement enhances energy autonomy, optimizes resource utilization, and minimizes dependence on the conventional grid, making the setup both sustainable and efficient.

Equation for DC Microgrid Power Supply

This is the foundational equation ensuring total power supply meets the demand and accounts for system dynamics:

Power Balance Equation

$$P_{PV} + P_S + P_G = P_{EVs} + C_{bus}\frac{dV_{bus}}{dt} \quad (1)$$

P_{PV}: Power from photovoltaic panels

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 12, April 2025
Impact Factor: 7.67

P_S: Power from or to storage system (positive = discharge)
P_G: Power from or to the public grid (positive = import)
P_{EVs}: Total power consumed by electric vehicles
C_{bus}: DC bus capacitance
$\frac{dV_{bus}}{dt}$: Rate of change of DC bus voltage

Available Power for EV Charging
This defines the upper limit of power that can be used for charging EVs at any given time:

$$P_{EVs\_lim} = P_{PV,MPPT} + P_{G,max} + P_{S,max} \quad (2)$$

$P_{PV,\,MPPT}$: PV power under maximum power point tracking
$P_{G,\,max}$: Maximum allowable grid power input
$P_{S,\,max}$: Maximum allowable power from the storage unit

Net Power Demand to Be Shared
Once PV contribution is known, remaining demand must be met by the grid and storage:

$$P^* = P_{EVs} - P_{PV} \quad (3)$$

P^*: Net required power from dispatchable sources
P_{EVs}: Actual EV charging power demand
P_{PV}: Actual real-time PV power generation

Power Distribution Equation
This splits the net required power between the battery storage and the grid:

$$P^* = P_S^* + P_G^* \quad (4)$$

P_S^*: Storage power contribution
P_G^*: Grid power contribution

Power Sharing Coefficient (k-factor)
This enables prioritization of energy sources, allowing for adaptive control:

$$P_S^* = k \,.\, P^*, \;\; P_G^* = (1-k).\,P^*, \;\; k \in [0,1] \quad (5)$$

k: Distribution factor—can be tuned dynamically to favor battery or grid
The above equations provide a complete mathematical foundation for simulating, analyzing, and managing energy flow in a DC microgrid-based EV charging station.

3.1 Photovoltaic (PV) Modeling
In the direct current microgrid, PV arrays serve as a RES and are interfaced with the direct current bus through a DC-DC converter. The PV system is modeled as a voltage-controlled current source whose behavior varies with solar irradiance and temperature. The Fig.2 shows the model of PV equivalent design.

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 12, April 2025
Impact Factor: 7.67

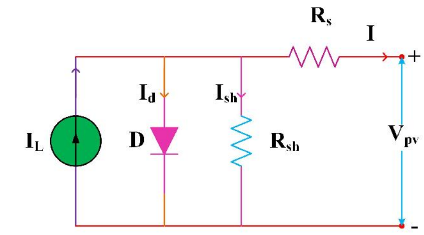


Fig.2 Equivalent Circuit of PV Model

$$C_{PV}\frac{dV_{PV}}{dt} = i_{PV} - i_{LPV} \tag{6}$$

$$L_{PV}\frac{di_{L_{PV}}}{dt} = v_{PV} - v'_{PV} \tag{7}$$

$$\begin{bmatrix} v'_{PV} \\ v'_{Lpv} \end{bmatrix} = m_{PV} \begin{bmatrix} v_{bus} \\ i_{LPV} \end{bmatrix} \tag{8}$$

V_{PV}: Voltage at the PV input
I_{PV}: Output current of the PV module
L_{PV}: Inductance in the PV converter
C_{PV}: Capacitance in the PV converter
m_{PV}: Converter duty cycle
V_{bus}: DC bus voltage

3.2 Public Grid Modeling

The public grid is modeled as a three-phase low-voltage AC network connected to the direct current bus through a bidirectional AC-DC converter (inverter). This converter handles synchronization, direct current voltage regulation, and bidirectional power exchange depending on system needs.
Inductive current dynamics (simplified per phase):

$$L\frac{di_{AC}}{dt} = v_{grid} - v'_{AC} \tag{9}$$

Bidirectional operation is achieved by adjusting the inverter control signals to allow import or export of power depending on P_{grid} sign.
V_{AC}: Grid-side voltage
I_{AC}: Grid-side current
v'_{AC}: DC-side voltages after conversion

3.3 Electric Vehicle (EV) Charging Modeling

The EV charging system uses a DC-DC converter to interface each vehicle battery with the direct current microgrid. The battery charging follows a CC/CV (Constant Current/Constant Voltage) profile and supports different charging modes: Fast, Average, and Slow. The charging mode determines the maximum power allocated to the EV.

$$C_{EV}\frac{dV_{EV}}{dt} = i_{L_{EV}} - i_{EV} \tag{10}$$

$$L_{EV}\frac{di_{L_{EV}}}{dt} = v'_{EV} - v_{EV} \quad (11)$$

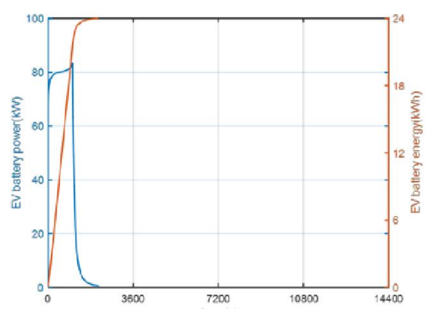
$$\begin{bmatrix} v'_{EV} \\ i'_{L_{EV}} \end{bmatrix} = m_{EV}\begin{bmatrix} v_{bus} \\ i_{L_{EV}} \end{bmatrix} \quad (12)$$

V_{EV}: Converter output voltage
I_{EV}: Converter output current
L_{EV}: Converter input Voltage
C_{EV}: Converter input Current
m_{EV}: Converter duty cycle
Each converter dynamically adjusts the charging rate based on user-selected mode and available power as shown in Table 1.
Each mode represents a different charging speed, offering users flexibility based on their time constraints and energy cost preferences.

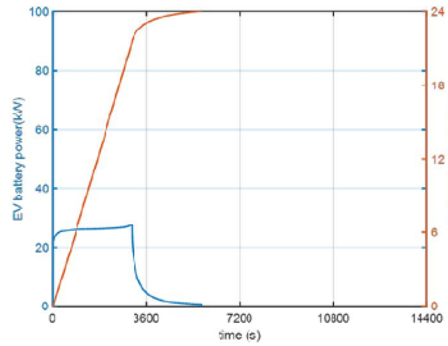
Table 1 Charging model with max. charging power

Charging Mode	Maximum Charging Power
Fast charging mode	P_{FAST_MAX}
Average charging mode	P_{AVER_MAX}
Slow charging mode	P_{SLOW_MAX}

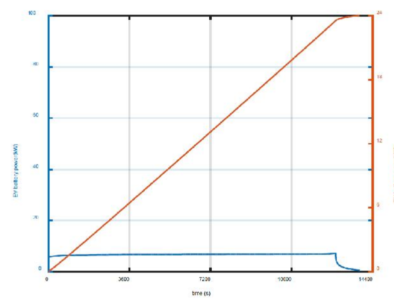
Fast Charging Mode corresponds to the highest power input level, denoted by P_{FAST_MAX} . This mode is designed to minimize charging time, typically preferred by users needing rapid turnaround. However, it places a greater load on the microgrid and may incur higher energy costs.
Average Charging Mode is represented by P_{AVER_MAX}. This setting provides a balanced approach between speed and energy consumption, making it suitable for users with moderate time availability and cost sensitivity.
Slow Charging Mode, denoted as P_{SLOW_MAX}, allows for minimal power delivery over an extended duration. It is the most energy-efficient and cost-effective option, ideal for long-duration parking or overnight charging scenarios.
This classification allows the energy management system to dynamically allocate power based on user preferences and available system capacity, enhancing overall operational efficiency while accommodating a wide behaviours and grid conditions.



(a)



(b)



(c)

Fig. 3 EV charging (a) Fast charging mode (b) Average charging mode (c) Slow charging mode

IV. EV CHARGING STATION MANAGEMENT STRATEGY

The Fig.4 illustrates the functional interaction between a direct current microgrid and an EV charging station, focusing on how the available energy supply influences the operational states of EV charging. On the left side, the microgrid consists of three primary sources: a PV system, an energy storage unit, and the public utility grid. These sources collectively determine the maximum power available for EV charging, denoted as P_{EVs_lim}. This value is computed based on current PV generation, the SOC of the battery, and the allowable input from the public grid.

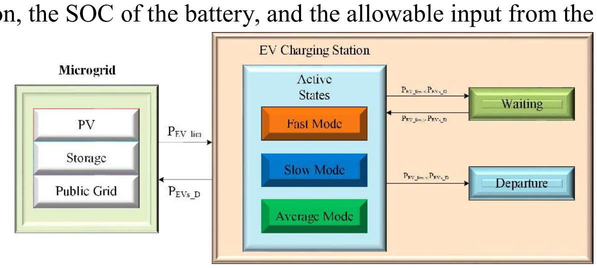


Fig.4 Interaction between a DC microgrid and EV charging station

The EV station operates based on predefined charging states categorized into Fast Mode, Average Mode, and Slow Mode. These modes represent different levels of charging power, selected by the user or dynamically assigned by the energy management system. The transition into these active states depends on whether the available power (P_{EV_lim}) is greater than the user-requested charging load demand (P_{EVs_D}). When sufficient power is available, the system activates the requested mode and proceeds with charging.

However, if the available power is less than the requested charging power (P_{EV_lim}<P_{EVs_D}), the system shifts the EV into a Waiting state, where it temporarily pauses charging until power becomes available. If the user is unwilling to wait or the deficit persists, the system leads to a Departure state, indicating that the user exits without charging. This

DOI: 10.48175/IJARSCT-25903

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429 Volume 5, Issue 12, April 2025 Impact Factor: 7.67

mechanism ensures adaptive control based on real-time conditions, promoting efficient energy utilization, reducing grid dependency, and enhancing the overall reliability of the EV charging process within a DC microgrid environment.

Table 2 Available Power Constraints in a DC Microgrid

The table 2 outlines the decision logic used by the EMS in a DC microgrid-based electric vehicle (EV) charging station. It maps the available power for EV charging, denoted as P_{EVs_lim}, to the feasible operational options for EVs based on predefined charging power thresholds. These thresholds P_{FAST_MAX} , P_{AVER_MAX}, and P_{SLOW_MAX} represent the minimum required power levels to support fast, average, and slow charging modes, respectively.

When the available power exceeds the fast-charging threshold ($P_{EVs\_lim}> P_{FAST\_MAX}$), all charging modes are accessible, giving users full flexibility to choose based on their needs. If the available power is less than the fast mode requirement but still sufficient for average charging ($P_{EVs\_lim}< P_{FAST\_MAX}$ and $P_{EVs\_lim}> P_{AVER\_MAX}$), the system restricts access to only the average mode, or alternatively allows the user to wait or leave. Similarly, if the power is insufficient for both fast and average modes but adequate for slow charging ($P_{EVs\_lim}< P_{AVER\_MAX}$ and $P_{EVs\_lim}> P_{SLOW\_MAX}$), only the slow mode is permitted, or the user may opt to wait or depart. In the case where the available power falls below the slow mode threshold ($P_{EVs\_lim}< P_{SLOW\_MAX}$), the system cannot initiate any charging process, and the user must choose either to wait or disconnect from the station.

4.1 EV Charging Decision Logic

When a new electric vehicle, or EV, comes at a charging station that is powered by a DC microgrid, the Fig. 5 flowchart shows the sequential reasoning that is followed. The main focus of the process of decision-making is to match the microgrid's available power,

represented by PEVs_lim, with the user's chosen charge mode—fast, average, or slow—and direct the subsequent activities accordingly.

When a new EV is delivered, the procedure starts, raising Question Q1: does the user select rapid, average, or slow charging? The system determines if there is sufficient power available for supporting that chosen mode based on this input.

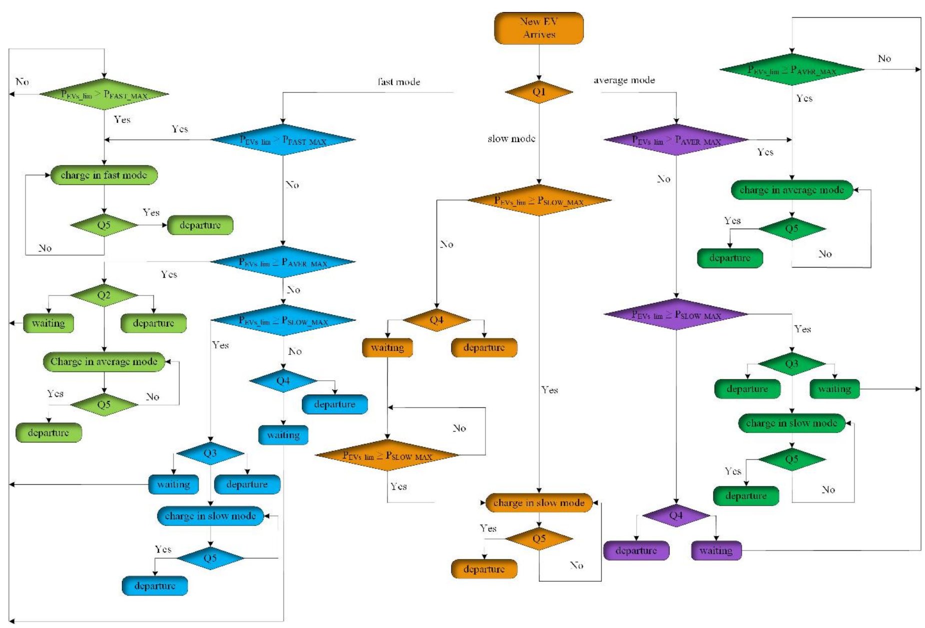


Fig 5. Power management flowchart of the EV charging station

The system determines whether the power that is accessible is higher or equal to the maximum needed for rapid charging ($P_{EVs\_lim}≥P_{FAST\_MAX}$) if the fast-charging option is chosen.

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 12, April 2025
Impact Factor: 7.67

If so, charging starts right away. The user is frequently prompted with Q5: "Do you want to stop and leave?" when charging. If so, the charging process is stopped. If not, it goes on.
If not, the system then determines whether slow or average charging is feasible. The user is presented with the option to wait, switch to average mode, or leave when Q2 is asked.

The system double-checks the availability of power
for typical charging ($P_{EVs\_lim} \geq P_{AVER\_MAX}$) if the user selects average mode.
If so, charging starts in average mode while Q5 continues to track the user's intention to disconnect.
If not, delayed charging viability is checked by the system. Q3 offers the motorist the option to wait or leave if only gradual charging is feasible.
• Charging starts if the user accepts slow mode and there is enough power.
• If not, Q4 ascertains whether the user would rather leave or wait for availability.
When the standard mode is first chosen, the system determines whether $P_{EVs\_lim} \geq P_{AVER\_MAX}$.
• If so, Q5 is used for monitoring as charging starts in average mode.
• If not, Q3 (wait or leave) or Q4 (power inadequate for any mode) are offered by the system after checking for support of slow modes.
The system determines whether there is sufficient power to support the slow mode if it is chosen from the beginning.
• If so, regular exit prompts (Q5) are displayed when charging starts in slow mode.
• If not, Q4 gives the motorist a choice between leaving the station or waiting for electricity.

V. SIMULATION RESULTS

The Fig.6 represents a microcontroller-based power management simulation developed in Proteus 8 Professional, designed to manage multiple power sources and loads intelligently. At the core of the system is an Arduino Uno (ARD1), which serves as the main control unit for decision-making and signal coordination.
On the left side of the schematic, three voltage sources are defined:
V1 (Solar Source)
V2 (Wind Source)
V3 (Generator Source)
Each of these source's feeds into a corresponding AC to DC rectifier and conditioning circuit, consisting of diodes (D1, D2, D3, etc.), resistors, capacitors, and zener diodes, which regulate and stabilize the input signal before it is processed by the microcontroller. These signals are routed to analog input pins on the Arduino for monitoring.
A PCF8574 (U2) I/O expander is used to extend the number of available digital inputs and outputs, interfacing with a 16x2 LCD display (LCD1) to show real-time data, such as voltage readings or load status.
Three relay modules (RL1, RL2, RL3) are used to switch loads (represented by L2, L3, L4) on and off. These relays are controlled by the Arduino based on logic programmed into its firmware, which likely considers the voltage level from each source and applies load priorities. Each relay is protected by flyback diodes to prevent damage during switching transients.

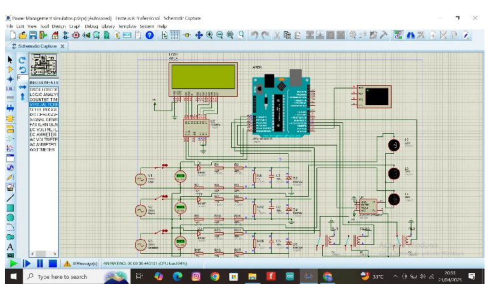


Fig.6 Simulation of Hybrid Power Management System

IJARSCT

International Journal of Advanced Research in Science, Communication and Technology

International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

ISSN: 2581-9429 Volume 5, Issue 12, April 2025 Impact Factor: 7.67

A serial terminal (top-right) allows data communication with a PC or other serial device for real-time debugging or data logging. This interface helps observe parameters such as current load status or input power source in use.

Overall, this simulation models a simplified smart energy management system, where power from multiple renewable and backup sources is intelligently controlled to supply critical loads efficiently. It demonstrates real-time monitoring, switching, and user feedback—key features in distributed energy systems and microgrid designs.

The Fig.7 demonstrates how an Arduino can be used to dynamically control the duty cycle of a power signal—commonly used in applications like battery charging, load regulation, or DC-DC converter systems.

At the centre of the circuit is an Arduino Uno (ARD1), which acts as the brain of the system. It generates a PWM (Pulse Width Modulated) signal that is used to control the operation of a power switch, typically a MOSFET (Q1), to regulate energy flow from the power source (BAT1) to the load (connected via BAT2 or output terminals).

A current sensing circuit is built using a low-side shunt resistor (visible near the current meter) and operational amplifier components (such as the optocoupler TLP250), which isolate and condition the signal before it is fed back into the Arduino's analog input for real-time monitoring.

The system includes:

Voltage and current feedback from the load to the Arduino,

A duty cycle adjustment algorithm running in the Arduino that responds to these inputs,

A serial terminal interface (Virtual Terminal) to display real-time parameters such as voltage, current, power, and PWM duty cycle,

Graphical oscilloscope outputs displaying current, voltage, and PWM signal behaviour over time.

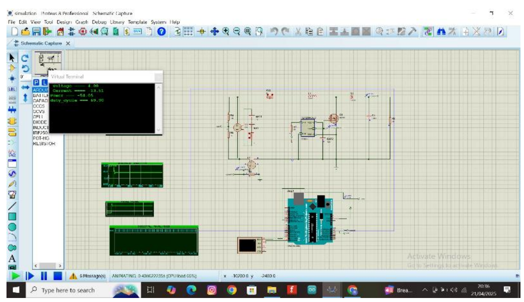


Fig.7 Arduino-controlled power regulation system

In the virtual terminal, we can observe that the duty cycle is actively managed (69.90%), with measured values of voltage (4.00V), current (-13.51A), and power (-54.05W). These values indicate the system is regulating output power under closed-loop control logic.

This simulation provides a practical visualization of how real-time measurements can be used to control power delivery in embedded systems. It has direct applications in renewable energy systems, battery management systems, and smart load control frameworks.

VI. HARDWARE RESULTS

The Fig.8 shows a hardware prototype of a solar-powered smart load management system, designed to demonstrate how solar energy can be effectively utilized to manage and control household or small-scale electrical loads using microcontroller-based automation.

A solar panel is prominently visible, which serves as the primary renewable energy source. The panel is connected to a solar charge controller, which regulates the voltage and current coming from the panel to safely charge connected batteries or power loads directly. This controller also protects the system against overcharging, deep discharge, and voltage spikes.

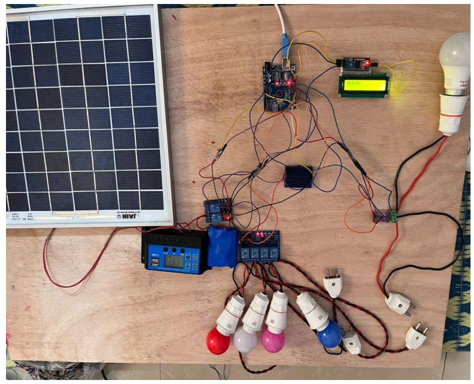


Fig. 8 Smart Solar Load Management System Using Arduino

Above the controller, an Arduino Uno microcontroller board is the brain of the system. It receives real-time sensor data and controls relay operations based on programmed conditions. To its left, a 16x2 LCD display is connected, likely used to display system status, voltage levels, or control messages.

Multiple relay modules are visible in the centre-right portion of the image. These relays act as electronically controlled switches that turn on or off various connected electrical loads—represented here by multiple bulb holders and coloured bulbs. Each relay is likely controlled by digital outputs from the Arduino, allowing the system to prioritize or shed loads depending on the available solar power or user-defined conditions.

Color-coded wiring connects various modules, and a DHT11 or DHT22 sensor (blue component near the Arduino) appears to be included for temperature and humidity monitoring, which could be used to assess environmental conditions that affect solar panel efficiency or system health.

A USB cable provides power or programming input to the Arduino from a computer. The presence of multiple plug sockets and connectors suggests modular flexibility, allowing for the easy addition or replacement of load devices.

Finally, the hardware results demonstrate a practical application of IoT and embedded control for energy-efficient smart home systems. It integrates renewable energy, sensor feedback, and automated load control, making it a powerful educational and functional model for decentralized energy management.

IX. CONCLUSION

This research provides a comprehensive control and optimization framework for electric vehicle (EV) charging stations integrated into DC microgrids. The proposed methodology leveraged renewable energy sources, storage systems, and intelligent load scheduling to enhance the performance, autonomy, and reliability of the charging infrastructure. A two-tier control strategy combining rule-based logic and mixed-integer linear programming was effectively applied to balance power supply and demand while adapting to varying user behaviour and resource availability.

Simulation results validated the efficiency of the framework in reducing grid dependency, improving energy utilization, and ensuring stable operation even under fluctuating conditions. The integration of adaptive decision-making, priority-based load restoration, and real-time power distribution demonstrated strong potential for supporting scalable and eco-friendly EV charging ecosystems. Future work could explore the implementation of advanced predictive control algorithms and real-time hardware testing to further improve the system's responsiveness and real-world applicability

REFERENCES

[1] Sayed, K., Abo-Khalil, A. G., & S. Alghamdi, A. (2019). Optimum resilient operation and control DC microgrid based electric vehicles charging station powered by renewable energy sources. Energies, 12(22), 4240.

[2] Wang, S., Lu, L., Han, X., Ouyang, M., & Feng, X. (2020). Virtual-battery based droop control and energy storage system size optimization of a DC microgrid for electric vehicle fast charging station. Applied Energy, 259, 114146.

[3] Mohammed, A. M., Alalwan, S. N. H., Taşcıkaraoğlu, A., & Catalão, J. P. (2022). Sliding mode-based control of an electric vehicle fast charging station in a DC microgrid. Sustainable Energy, Grids and Networks, 32, 100820.

[4] Mohan, H. M., & Dash, S. K. (2023). Renewable energy-based DC microgrid with hybrid energy management system supporting electric vehicle charging system. Systems, 11(6), 273.
[5] Abraham, D. S., Chandrasekar, B., Rajamanickam, N., Vishnuram, P., Ramakrishnan, V., Bajaj, M., ... & Prokop, L. (2023). Fuzzy-based efficient control of DC microgrid configuration for PV-energized EV charging station. Energies, 16(6), 2753.
[6] Savio Abraham, D., Verma, R., Kanagaraj, L., Giri Thulasi Raman, S. R., Rajamanickam, N., Chokkalingam, B., ... & Mihet-Popa, L. (2021). Electric vehicles charging stations' architectures, criteria, power converters, and control strategies in microgrids. Electronics, 10(16), 1895.
[7] Zaid, S. A., Bakeer, A., Albalawi, H., Alatwi, A. M., AbdelMeguid, H., & Kassem, A. M. (2023). Optimal fractional-order controller for the voltage stability of a DC microgrid feeding an electric vehicle charging station. Fractal and Fractional, 7(9), 677.
[8] Faraji, H., Khorsandi, A., & Hosseinian, S. H. (2023). Multi-level coordinated control of islanded DC microgrid integrated with electric vehicle charging stations with fault ride-through capability. Journal of Cleaner Production, 420, 138372.
[9] Savio, A. D., Balaji, C., Kodandapani, D., Sathyasekar, K., Naryanmoorthi, R., Bharatiraja, C., & Twala, B. (2022). DC microgrid integrated electric vehicle charging station scheduling optimization. Journal of Applied Science and Engineering, 26(2), 253-260.
[10] Savio, D. A., Juliet, V. A., Chokkalingam, B., Padmanaban, S., Holm-Nielsen, J. B., & Blaabjerg, F. (2019). Photovoltaic integrated hybrid microgrid structured electric vehicle charging station and its energy management approach. Energies, 12(1), 168.
[11] Aluisio, B., Dicorato, M., Ferrini, I., Forte, G., Sbrizzai, R., & Trovato, M. (2019). Optimal sizing procedure for electric vehicle supply infrastructure based on DC microgrid with station commitment. Energies, 12(10), 1901.
[12] Krishnamurthy, N. K., Sabhahit, J. N., Jadoun, V. K., Gaonkar, D. N., Shrivastava, A., Rao, V. S., & Kudva, G. (2023). Optimal placement and sizing of electric vehicle charging infrastructure in a grid-tied DC microgrid using modified TLBO method. Energies, 16(4), 1781.
[13] Cleenwerck, R., Azaioud, H., Vafaeipour, M., Coosemans, T., & Desmet, J. (2023). Impact assessment of electric vehicle charging in an AC and DC microgrid: A comparative study. Energies, 16(7), 3205.
[14] Pan, H., Feng, X., Li, F., & Yang, J. (2023). Energy coordinated control of DC microgrid integrated incorporating PV, energy storage and EV charging. Applied Energy, 342, 121155.
[15] Sowrirajan, N., Karthikeyan, N., Dharmaprakash, R., & Kumar, S. S. (2025). Enhancing electric vehicle charging stations in DC microgrid using KOA–DRN approach. Electrical Engineering, 107(3), 2983-2996.